BOOKS BY GEORGE ELLERY HALE

SIGNALS FROM THE STARS

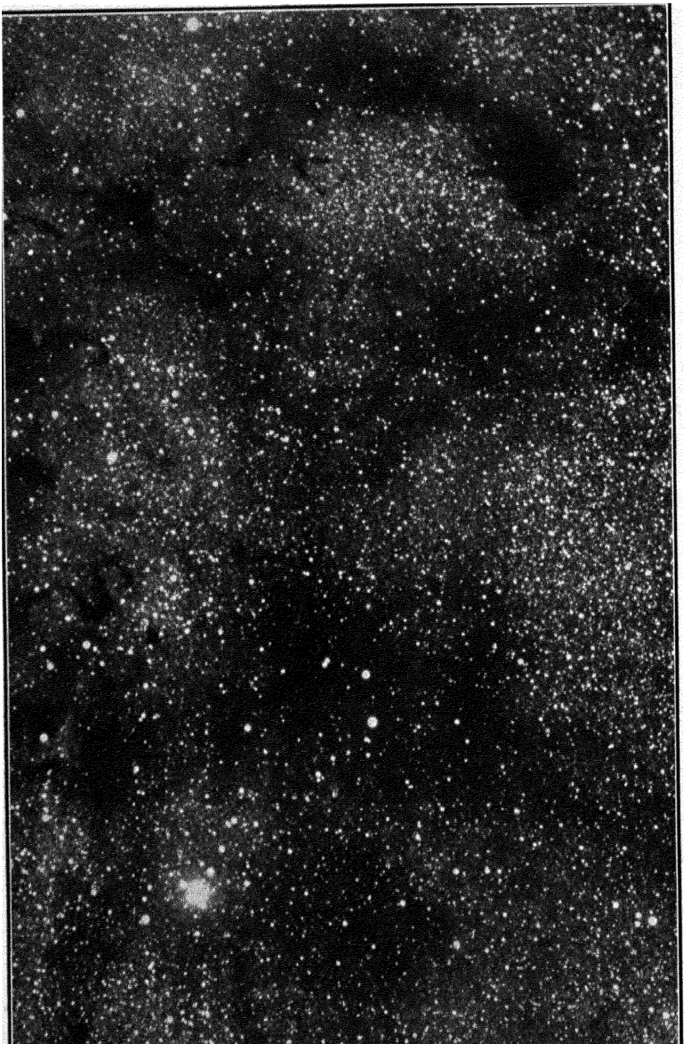
BEYOND THE MILKY WAY

THE DEPTHS OF THE UNIVERSE

THE NEW HEAVENS

CHARLES SCRIBNER'S SONS

SIGNALS
FROM THE STARS



Star clouds in the Milky Way. (Barnard.)

SIGNALS
FROM THE STARS

BY

GEORGE ELLERY HALE

HONORARY DIRECTOR OF THE MOUNT WILSON OBSERVATORY
OF THE CARNEGIE INSTITUTION OF WASHINGTON

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A

TO

H. M. R.

PREFACE

Signals from the stars, of the greatest variety and significance, are constantly reaching the earth. An outburst on the face of the sun, made visible by the spectrohelioscope, may forecast a brilliant aurora and affect radio transmission. The rhythmic rise and fall of the light of faint variable stars in remote spiral nebulæ, enfeebled by distance but within the range of the largest telescopes, affords a vital clue to the structure of the universe. The observation and decipherment of these and countless other celestial events is a fascinating task, demanding the joint efforts of astronomers, mathematicians, physicists, chemists and geophysicists, powerfully equipped by opticians, instrument-makers and engineers.

In previous volumes* I have described this task, since extended to new and puzzling phenomena. Small telescopes as well as large ones may play important parts in some phases of the work, which call for international co-operation among both amateur and professional observers. Thus the present book, which deals primarily with the possibilities of very large telescopes, also emphasizes attractive opportunities recently opened to small instruments. Its chapters, in somewhat different form, originally appeared in *Scribner's* and *Harpers* magazines and in *Popular Astronomy.* I owe

*"The New Heavens," "The Depths of the Universe" and "Beyond the Milky Way."

my acknowledgments to the publishers of these journals, to the Director and staff of the Mount Wilson Observatory, and to all those who have aided me by supplying information and illustrations for use in the text.

G. E. H.

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SIGNALS
FROM THE STARS

Chapter I

THE POSSIBILITIES OF LARGE TELESCOPES

Like buried treasures, the outposts of the universe have beckoned to the adventurous from immemorial times. Princes and potentates, political or industrial, equally with men of science, have felt the lure of the uncharted seas of space, and through their provision of instrumental means the sphere of exploration has rapidly widened. If the cost of gathering celestial treasure exceeds that of searching for the buried chests of a Morgan or a Flint, the expectation of rich return is surely greater and the route not less attractive. Long before the advent of the telescope, pharaohs and sultans, princes and caliphs built larger and larger observatories, one of them said to be comparable in height with the vaults of Santa Sophia. In later times kings of Spain and of France, of Denmark and of England took their turn, and more recently the initiative seems to have passed chiefly to American leaders of industry. Each expedition into remoter space has made new discoveries and brought back permanent additions to our knowledge of the heavens. The latest explorers have worked beyond the boundaries of the Milky Way in the realm of spiral "island universes," the first of which lies nearly a million light-years from the earth while the farthest is immeasurably remote. As yet we can barely discern a few of the countless suns in the nearest of these spiral sys-

tems and begin to trace their resemblance with the stars in the coils of the Milky Way. While much progress has been made, our greatest hopes still lie in the future.

Nothing is more encouraging to the scientific investigator than the rapid multiplication in recent years of the possibilities of instrumental development. In astronomy the opportunities for advance have been vastly enlarged by the remarkable progress of physics and chemistry, and the many new instruments and methods thus rendered available. To appreciate our advantages, we have only to glance rapidly over the history of science and contrast present possibilities with those of the past.

INSTRUMENTS AND PROGRESS

The beginning of the new year, practically coinciding with the annual inundation of the Nile, was fixed by observations of the heliacal rising of Sirius before 4000 B. C. Throughout their entire history the Egyptian priests were astronomers, yet their sundials, water clocks, and the crude "Merkhet," a measuring instrument for determining the time from observations of stars near the meridian, apparently underwent no important improvement down to the Greek occupation of Egypt.* The Babylonians, although much more effective observers than the Egyptians, left us no instruments. The Greeks invented several instruments, which are described by Ptolemy in the Almagest.

*Many of the historic instruments mentioned here are illustrated in the author's book, "Beyond the Milky Way."

Most of these consist essentially of a graduated arc of a circle, provided with adjustable sights and supported in the plane of observation. So completely did these instruments embody the ingenuity of the Greeks that they were adopted without important change by the Arabs, Hindus, and Chinese, and served for the equipment of Tycho Brahe's great observatory in the period of revival of the sixteenth century. Tycho devoted special attention to the improvement of instruments, which he constructed in his own shops. But though spectacles had been worn since the end of the thirteenth century, he little suspected the great opportunity they placed before him.

The history of lenses is full of interest. I have examined at the British Museum the disc of rock crystal, oval in shape and roughly ground to a plano-convex form, which was found by Layard in Sargon's palace at Nimroud, and do not believe it was intended for use as a lens, in spite of Sir David Brewster's contrary opinion. Nor can it be surely affirmed from their minuteness of detail and perfection of execution that the finely engraved gems of antiquity were cut under lenses. Pliny the elder and others state that globes filled with water were used as burning glasses, and Seneca remarks that "letters though small and indistinct are seen enlarged and more distinct through a globe of glass filled with water." Yet while defects of vision were frequently discussed by many classic authors, they made no reference to the simplest optical aids, and myopia was repeatedly declared to be incurable down to the end of the thir-

teenth century, when spectacles first came into use.

Roger Bacon and his teacher, Grossteste, undoubtedly understood some of the properties of lenses and concave mirrors, but the evidence advanced to support the opinion that Bacon used telescopes for astronomical observations is not convincing. The early history of the telescope remains rather obscure, but from our point of view the most important fact is its application in astronomy by Galileo and the revolution in human thought effected by his discoveries. His sudden recognition and utilization of a principle which had been partially applied in the case of spectacles for three hundred years quickly transformed the equipment of the observatory and laid the foundation of astrophysical research. In 1630 Francesco Generini saw the feasibility of using the telescope for increased precision in pointing, presumably by introducing threads into the focal plane of the eyepiece. About ten years later the inventor of the micrometer undoubtedly used this method. The modern period of astronomical measurement was thus begun.

As for the telescope itself, it was first improved by the invention of the Keplerian eyepiece and then increased in focal length to overcome the troublesome effects of aberration. Rayleigh has shown that a single lens of 1.7-inch aperture, when its focus is 66 feet, is as good as an achromatic. Huygens, who worked out the theory of chromatic aberration, greatly increased the aperture and focal length of his telescopes. He also devised the Huygenian eyepiece and was rewarded for his efforts by the discovery of

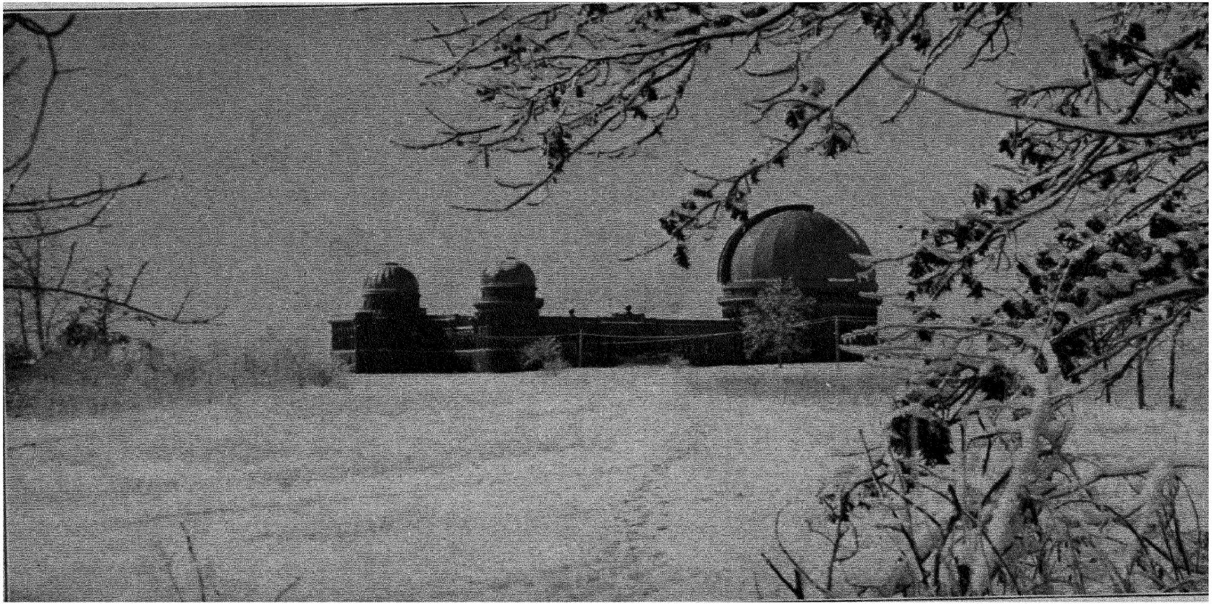

Fig. 1. The Yerkes Observatory of the University of Chicago.

the true nature of the rings of Saturn. Three of his objectives, with focal lengths of 122, 170, and 210 feet, respectively, are still in the possession of the Royal Society. Telescopes up to 600 feet in length were made in this period, but the difficulty of finding and following the celestial object seriously affected their value. Obviously, they could not be carried on equatorial mountings, first described for telescopic purposes in Scheiner's Rosa Ursina, but really not different in principle from the equatorial armilla of Tycho Brahe. An accessory of the hightest importance constructed at this time was the pendulum clock, developed by Huygens following Galileo's discovery of isochronism.

Two steps taken for the purpose of overcoming chromatic aberration ultimately proved successful. The reflecting telescope, introduced by Gregory and Newton, reached apertures of 4 feet in the hands of Herschel and 6 feet in those of Lord Rosse. The invention of the achromatic objective, followed by the production of optical glass in larger and larger discs, made way for the great refractors of the present day. Their high perfection, like that of the modern reflector, is the result of successive advances in the art of the glass maker, the metallurgist, the mechanical engineer, and the optician, and the development of modern machine tools, which Lord Rosse did not possess. Even if the photographic plate had then been perfected, the absence of an accurately driven equatorial mounting would have rendered it useless with his 6-foot reflector. The refinement and pre-

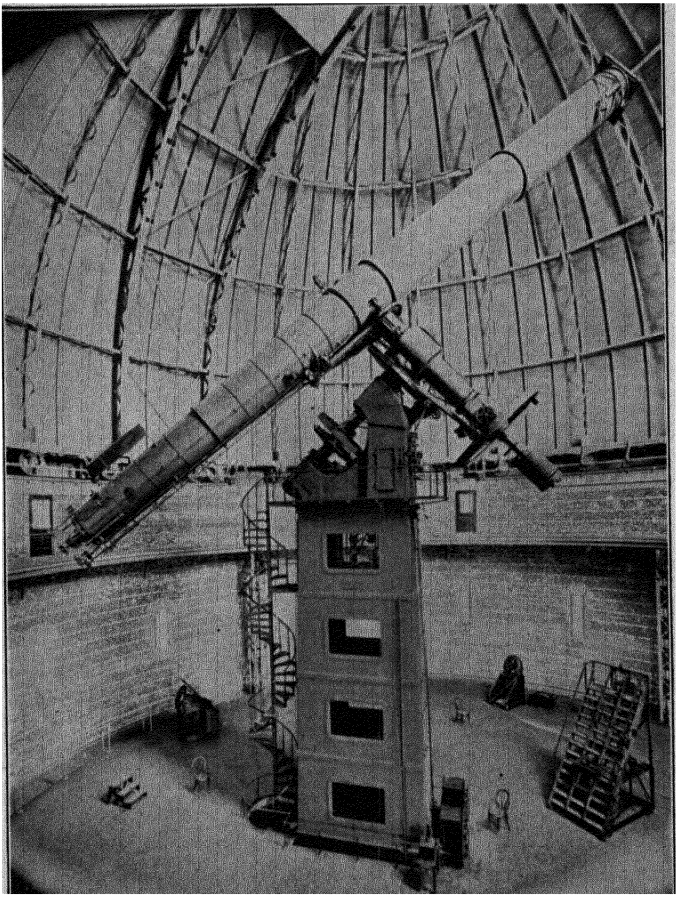

Fig. 2. The 40-inch refractor of the Yerkes Observatory. The elevating floor is shown at its lowest position.

cision of the modern meridian circle, with its nearly perfect pivots and beautifully graduated circles, is another result of the improved art of the instrument

maker, which is also illustrated in such valuable accessories as the latest types of clocks, the recording chronograph, and the moving wire micrometer.

The first telescopes collected about 80 times as much light as the unaided eye, and this light-gathering power has now been increased to about 200,000 times that of the eye. As the quality of the atmosphere and the optical and mechanical perfection of the best modern instruments are sufficiently good to permit all of this light (barring losses by reflection) to be concentrated and held in a very small image, the gain thus effected is enormous. But the advantages derived from the introduction and improvement of the photographic plate, and the development of many auxiliary instruments and methods, are no less important.

THE SPECTROSCOPE

When Newton decomposed sunlight with a prism in 1672, he took the first great step in the initiation of spectroscopy. It was not until 1803, however, that Wollaston detected the principal dark lines in the solar spectrum, nearly 600 of which were measured by Fraunhofer in 1814. Their interpretation by Stokes, who, in 1852, recognized that the double D line is due to sodium vapor, which absorbs the same radiations that it emits, and later by Kirchhoff and Bunsen, who, in 1859, identified many terrestrial elements in the sun, provided the means of determining the chemical composition of celestial objects.

The study of stellar evolution, foreshadowed by Herschel and by Laplace in the nebular hypothesis,

was thus rendered possible in the very year of the publication of Darwin's "Origin of Species." This was a tremendous advance, even when only the classification of stellar spectra, at once undertaken by Secchi and Huggins, and the apparent variation of chemical composition with stellar evolutional progress, are considered. But the chief significance of the adoption of the spectroscope in the observatory lies in the extraordinary versatility of this instrument, and the possibilities it affords of utilizing in astronomy the widest variety of physical and chemical discoveries.

In 1842 Doppler tried to prove that the color of a star depends upon its velocity. Rightly applied with the spectroscope, his principle has given us the means of measuring the motions of gases in the solar atmosphere; the rotation of the sun, planets, and nebulæ; the orbital velocity of close double stars discoverable only by this method; and the velocity in the line of sight of various celestial objects.

I wish that space permitted me to dwell on the extraordinary harvest which has resulted from the skilful application of this and other principles of physics, but I may recall only a few of them. The shift toward red or violet of spectral lines by pressure affords a means of measuring the pressure in stellar atmospheres, after other effects have been allowed for. The variation of the relative intensities of lines with temperature gives one clue to stellar temperatures, and also led indirectly to Adams' beautiful method of deriving absolute magnitudes and parallaxes from stellar spectra. Reduced to a sound scientific basis

through the recent advances of physics, the study of line intensities has also become one of our most powerful guides, not only to the nature of stars but to the

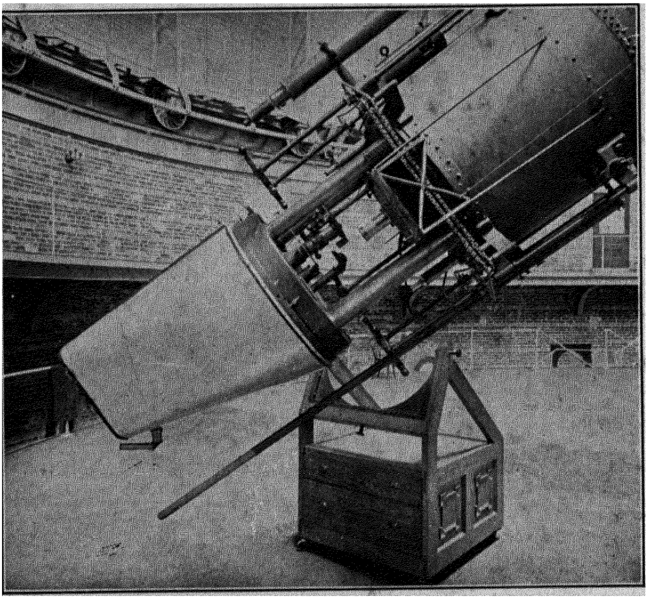

Fig. 3. Three-prism stellar spectrograph attached to the 40-inch Yerkes refractor.

structure of the atom itself. The shift of the maximum of intensity in the spectrum as a function of the temperature, the influence of magnetic and electric fields on radiation, the phenomena of polarization, of anomalous dispersion, and of optical resonance are also among the numerous discoveries of the physicist which the astronomer has already utilized, with important positive or negative results.

In addition to the spectroscope, the astronomer has derived from the physical laboratory a long line of other valuable instruments. The photometer, now powerfully supplemented and largely displaced by photographic methods, has given us the magnitudes of tens of thousands of stars. The thermopile, bolometer, and radiometer have led to remarkable advances in our knowledge of the infra-red spectrum, the precise measurement of the varying intensity of the solar radiation, the determination of the heat radiation of stars as faint as the thirteenth magnitude, and even to studies of the energy spectra of some of the brighter stars. The photo-electric cell has yielded stellar photometric measures of surprising precision. The radiometer, which gave the first actual measure of the pressure of radiation, now known to play such a dominant part in stars, provided the means of detecting the last wave-lengths missing in the long range from the gamma rays to radio waves 20,000 meters in length. The interferometer, springing from Young's famous interference experiment of more than a century ago, has served for scores of brilliant successes, recently culminating in the determination of the diameters of giant stars.

Without attempting to enumerate more of the astronomer's long list of debts to the physicist and chemist, let us look for a moment at the increase in the precision of measurement effected by instrumental advances. The star places of the Greeks were given to the nearest 10 minutes of arc, one-third the diameter of the moon. Tycho succeeded in reducing

the probable error of a single measure of the distance between two neighboring stars to 57 seconds. In double star observations the probable errors of the best micrometric measures are about 0.1 seconds. In modern photographic parallax determinations the probable error is about 0.005 seconds to 0.010 seconds. With the interferometer, the probable error of a single measure of the separation of the components of Capella is 0.001 seconds. The diameter of Arcturus, 0.019 seconds, can be similarly measured with a probable error of about the same amount.

The advantages to be gained by the early utilization of the rapid progress of the physicist and chemist are obvious. Almost any discovery may help us directly or indirectly. We are interested in new organic dyes because they may improve the sensitiveness of our plates in various regions, especially in the infra-red, where extraordinary progress has recently been made. We earnestly hope for a reduction in the size of the grain of the most rapid photographic plates, which would be equivalent to a marked increase in the aperture of our telescopes. We keenly watch for the appearance of new alloys, perhaps suitable for telescope mirrors or for the special needs of optical gratings; progress in the manufacture of optical glass; the production of large masses of fused quartz for prisms or mirrors—every technical advance, in fact, that we can learn to utilize. And we are equally anxious to benefit by the constant improvement of high-tension transformers, electric furnaces, vacuum tubes, electromagnets, and the many other devices on which we

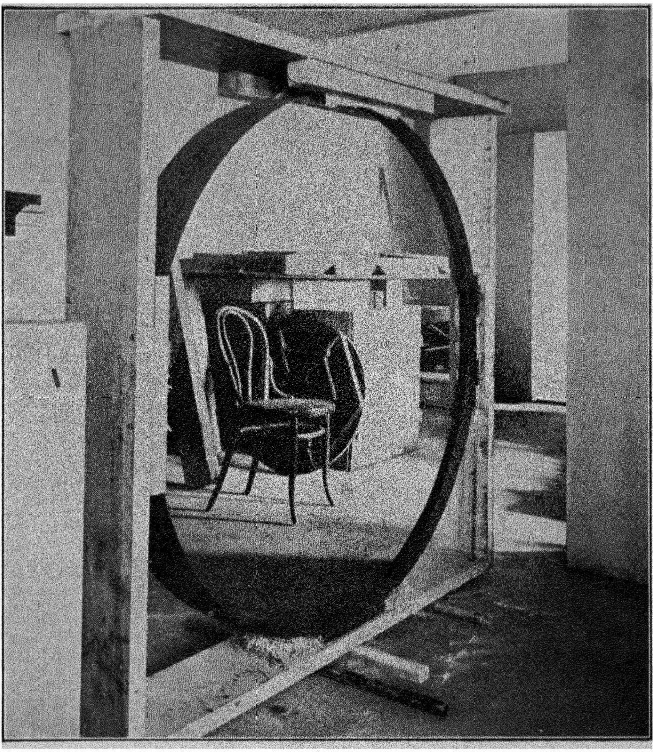

Fig. 4. 60-inch glass disc for the Mount Wilson reflector.

depend for the imitation and interpretation of celestial phenomena.

These illustrations of the increasing possibilities of instrumental development have not been enumerated in strict chronological sequence, but a glance at this partial list will show how rapidly the opportunities of the astronomer have multiplied in recent years. Another point should be noted: The obvious chance is

not always the most important one, and the greatest advances may come from the recognition of possibilities that are not immediately apparent. Hence the astronomer cannot watch too intently the progress of related sciences, and especially the numerous devices and methods which are constantly arising in various fields. Such beautiful new instruments as the X-ray spectrograph or the mass spectrograph of Aston, while perhaps not directly applicable in astronomy, may contain hints, and also yield results, which can be used to advantage.

The above considerations will help to explain the somewhat unorthodox equipment and policy of the Mount Wilson Observatory. We have tried from the outset, with the valuable co-operation of our research associates, to utilize the increasing possibilities offered by the progress of physics and chemistry, and to gain such advantages as laboratory conditions and methods have placed at our disposal. Hence the design of the Snow and tower telescopes, equipped for solar research; the coudé principle and the constant temperature laboratories of the 60-inch and 100-inch reflectors, arranged for the photography of stellar spectra under high dispersion, and for investigations like those with the thermopile, bolometer, and radiometer on stellar radiation and energy spectra; the exceptional care taken to secure smooth rotation of the 100-inch dome in order to diminish the vibration of the high dispersion stellar spectrograph during exposures continued for several nights; the construction of the ruling machine, one of the prime purposes of

which is to permit such experiments as may render possible the concentration of most of the incident light in any desired order of spectrum; the development of the stellar interferometer, first in conjunction with the 100-inch telescope and now as a separate instrument. Hence the provision of machine and optical shops adequate for a wide range of constructional work and a physical laboratory in which to conduct researches required for the interpretation of celestial phenomena. Hence also our close co-operation with the California Institute of Technology, the recent growth of which as a research institution is so advantageous to the Mount Wilson Observatory.

LARGE TELESCOPES

Looking ahead, and speculating on the possibilities of future instruments, it may be mentioned that comparative tests of the 60-inch and 100-inch telescopes promise well for larger apertures. Much can be done with small telescopes, as I shall show in succeeding chapters, but in dealing with the most vital problems of the nature and evolution of stars and the structure of the universe we are still hampered by insufficient light, which can be supplied only by larger telescopes.

I have had more than one chance to appreciate the enthusiasm of the layman for celestial exploration. Learning in August, 1892, that two discs of optical glass, large enough for a 40-inch telescope, were obtainable through Alvan Clark, I informed President Harper of the University of Chicago, and we jointly presented the opportunity to Mr. Charles T. Yerkes.

He said he had dreamed since boyhood of the possibility of surpassing all existing telescopes, and at once authorized us to telegraph Clark to come and sign a contract for the lens. Later he provided for the telescope mounting and ultimately for the building of the Yerkes Observatory at Lake Geneva, Wisconsin.

In 1903, after the Yerkes Observatory was in full operation, and many unsuccessful attempts had been made to obtain a still larger telescope, I began work on a small scale at the summit of Mount Wilson, where a committee of the Carnegie Institution of Washington had found exceptionally favorable observational conditions. The results interested the trustees of the Institution and revived our project for a large observatory there. Three years later Mr. John D. Hooker of Los Angeles, a business man interested in astronomy, agreed to meet the cost of making the optical parts for an 84-inch reflecting telescope in the shops of the Mount Wilson Observatory in Pasadena, where a 60-inch mirror had recently been figured by Ritchey. Before the glass could be ordered he increased his gift to provide for a still larger mirror. Half a million dollars was still needed for the mounting and observatory building, and Mr. Carnegie, who was greatly taken with the project during his visit to the Observatory in 1910, wanted the Carnegie Institution of Washington to supply it. The entire income of the Institution was required, however, to provide for the annual expenses of its ten departments of research, of which the Observatory is one. Nearly a year later, after further talks

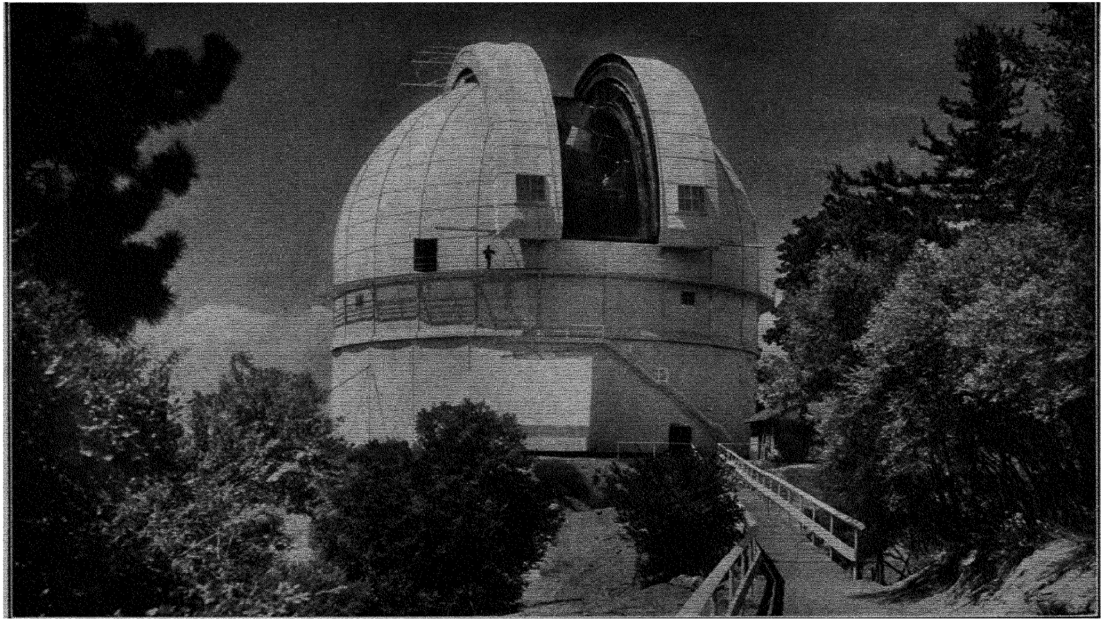

Fig. 5. Dome of the 100-inch Hooker reflecting telescope of the Mount Wilson Observatory.

with Mr. Carnegie, I was on my way to Egypt. At Ventimiglia, on the Italian frontier, I bought a local newspaper, in which an American cable had caught my eye. Mr. Andrew Carnegie, by a gift of $10,000,000, had doubled the endowment of the Carnegie Institution of Washington. A paragraph in his letter to the trustees especially appealed to me: "I hope the work at Mount Wilson will be vigorously pushed, because I am so anxious to hear the expected results from it. I should like to be satisfied before I depart, that we are going to repay to the old land some part of the debt we owe them by revealing more clearly than ever to them the new heavens."

I trust that the 100-inch Hooker telescope, thus named at Mr. Carnegie's special request, has justified his expectations. Its results, described in part in "The New Heavens," "The Depths of the Universe," and "Beyond the Milky Way," have certainly surpassed our own forecasts. They have given us new means of determining stellar distances, a greatly clarified conception of the structure and scale of the Galaxy, the first measures of the diameter of stars, new light on the constitution of matter, new support for the Einstein theory, and scores of other advances. They have also made possible new and surprising researches beyond the boundaries of the Milky Way in the region of the spiral nebulæ. Moreover, they have convinced us of the need of a much larger telescope to extend the range of exploration farther into space. Lick, Yerkes, Hooker, and Carnegie have passed on, but the opportunity remained for some other donor to

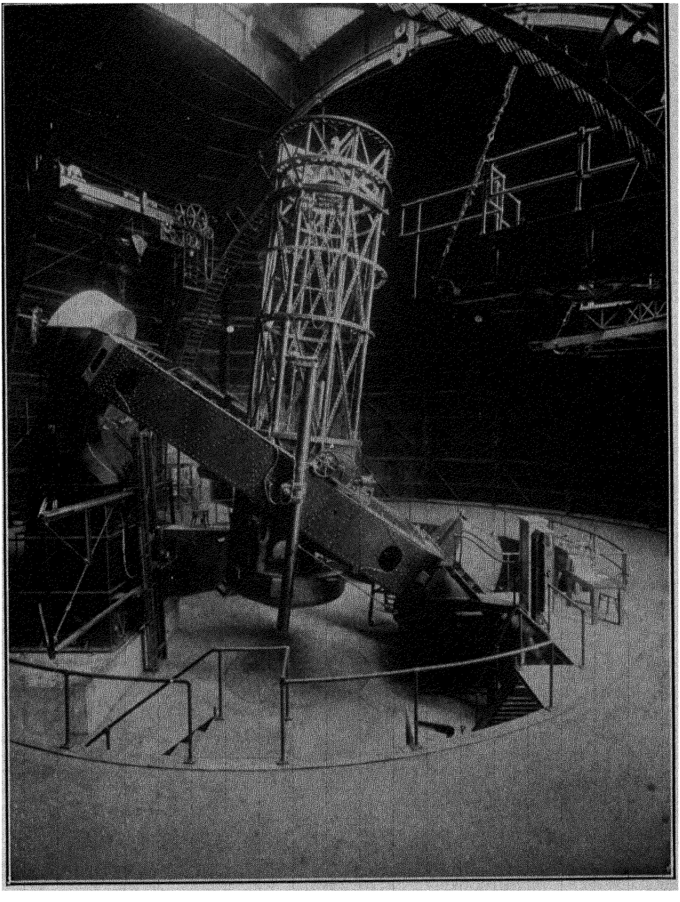

Fig. 6. The 100-inch Hooker telescope.

advance knowledge and to satisfy his own curiosity regarding the nature of the universe and the problems of its unexplored depths.

El Karakat, an Arabian astronomer who built a

great observatory at Cairo in the twelfth century, once exclaimed to the Sultan, "How minute are our instruments in comparison with the celestial universe!" In his day the amount of light received from a star was merely that which entered the pupil of the eye, and large instruments were constructed, not with any idea of discovering new celestial objects, but in the hope of increasing the precision of measuring the positions of those already known. Galileo's telescope, which suddenly expanded the known stellar universe at the beginning of the seventeenth century, had a lens about 2¼ inches in diameter, with an area 80 times that of the pupil of the eye. This increase in light-collecting power was sufficient to reveal nearly half a million stars (over the entire heavens), as compared with the few thousands previously within range. The 100-inch mirror of the Hooker telescope, which collects about 200,000 times as much light as the eye, is capable of recording photographically about 1,500 million stars.

While the gain since Galileo's time seems enormous, the possibilities go far beyond. Starlight is falling on every square mile of the earth's surface, and the best we can do at present is to gather up and concentrate the rays that strike an area 100 inches in diameter. From an engineering standpoint our telescopes are small affairs in comparison with modern battleships and bridges. There has been no such increase in size since Lord Rosse's 6-foot reflector, completed in 1845, as engineering advances would permit, though advantage has been taken of the possible

gain in precision of workmanship. A further advance is undoubtedly due.

NEW POSSIBILITIES

I have never liked to predict the specific possibilities of large telescopes, but the present circumstances are so different from those of the past that less caution seems necessary. The astronomer's greatest obstacle is the turbulence of the earth's atmosphere, which envelops us like an immense ocean, agitated to its lowest depths. The crystal-clear nights of frosty winter, when celestial objects seem so bright, are usually the very worst for observation. Watch the excessive twinkling of the stars, and you will appreciate why this is true. In a perfectly quiet and homogeneous atmosphere there would be no twinkling, and star images would remain sharp and distinct even when greatly magnified. Mixed air of varying density means irregular refraction, which causes twinkling to the eye and boiling images, blurred and confused, in the telescope. Under such conditions a great telescope may be useless.

This is why Newton wrote in his "Opticks":

"If the Theory of making Telescopes could at length be fully brought into practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fix'd stars. The only remedy is a most serene and quiet Air, such as

may perhaps be found on the tops of the highest Mountains above the grosser Clouds."

Even at the best of sites, in a climate marked by long periods of great tranquillity, unbroken by storms, the atmosphere remains the chief obstacle. For this reason we could not be sure how well the 60-inch and 100-inch reflecting telescopes would work on Mount Wilson until we had rigorously tested them. Large lenses or mirrors, uniting in a single image rays which have travelled through widely separated paths, are more sensitive than small ones to atmospheric tremor. So it has always been a lottery, as we frankly told the donors of the instruments, whether the next increase in size might not fail to bring the advantages we sought.

Fortunately we have found, after several years of constant use, that on all good nights the gain of the 100-inch Hooker telescope over the 60-inch is fully in proportion to its greater aperture. The large mirror receives and concentrates in a sharply defined image nearly three times as much light as the smaller one, with consequent immense advantages. But the question remains whether we can now safely advance to an aperture of 200 inches.

Our affirmative opinion is based not merely upon the performance of the Hooker telescope, but also upon tests of the atmosphere made with apertures up to 20 feet. The Michelson stellar interferometer, with which Pease has succeeded in measuring the diameters of several stars, is attached to the upper end of the tube of the Hooker telescope. When its two outer

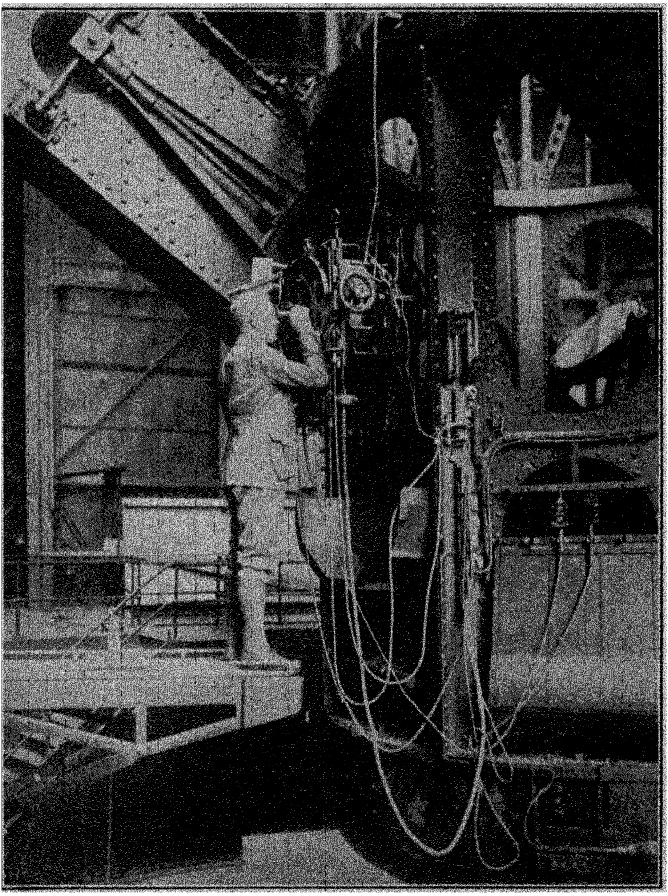

Fig. 7. Observing with the 100-inch telescope.

mirrors are separated as far as possible, they unite in a single image beams of starlight entering in paths 20 feet apart. By comparing these images with those observed when the mirrors are 100 inches or less apart,

Pease concludes that an increase of aperture to 20 feet or more would be perfectly safe. For the first time, therefore, we can make such an increase without the uncertainties that have been unavoidable in the past.

Other reasons that combine to assure the success of a larger telescope are the remarkable opportunities for new discoveries revealed by recent astronomical progress and the equally remarkable means of interpreting them afforded by recent advances in physics and chemistry.

These new possibilities are so numerous that I must confine myself to a few general examples, bearing upon the structure of the universe, the evolution of stars, and the constitution of matter. A 200-inch telescope would give us 4 times* as much light as we now collect with the 100 inch. How would this help in dealing with these questions?

The first advantage that strikes one is the immense gain in penetrating power and the means thus afforded of exploring remote space. The spiral structure of nebulæ beyond the Milky Way was unknown until Lord Rosse discovered it with his 6-foot reflector in 1845. The Hooker telescope, greatly aided by optical and mechanical refinements and by the power of photography, can now record perhaps 2,000,000 of these remarkable objects. Moreover, in the hands of Hubble it has proved that they are in fact remote stellar systems, similar in structure to the Galaxy, of which our solar system is an infinitesimal part.

Our present instruments are thus powerful enough

*Ten times as much, in effect, if we use a shorter relative focal length.

to give us this imposing picture of a universe dotted with isolated systems, some of them certainly containing millions of stars brighter than our sun. It is also possible to measure accurately the distance of the Great

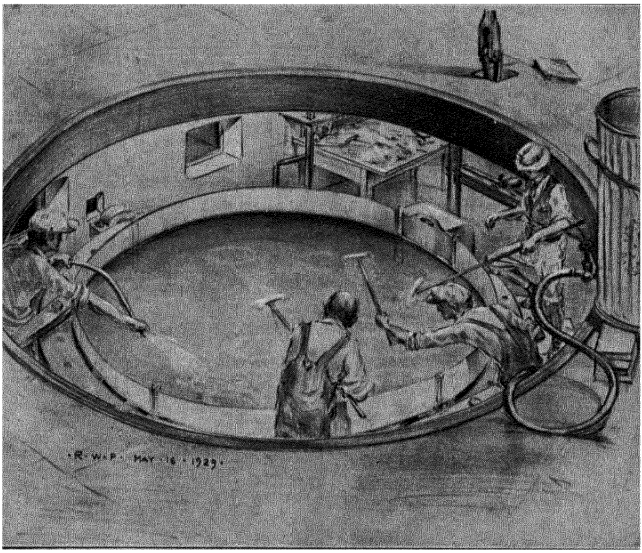

Fig. 8. Cleaning the 100-inch mirror before silvering. From a sketch by Russell W. Porter.

Nebula in Andromeda and one or two other spirals that lie about a million light-years from the earth. Much larger telescopes are needed, however, to continue the analysis of these nearest spirals, now only just begun, and to extend it to those at greater distances. Most interesting of all will be the interpretation of the apparent outward flight of these spirals, which

seem to be receding from us at almost incredible velocities, increasing with their distance (see page 126). Needless to say, the greater power of larger telescopes would also give us a far better understanding than we now possess of the structure and nature of the Galaxy, of which we still have much to learn. For example, we cannot yet say whether it shares the characteristic form of the spiral nebulæ, though it is probable that it rotates about its centre at the enormous velocity that seems equally characteristic of the "island universes." In fact, our own stellar system offers countless opportunities for productive research, as the latest advances in our knowledge of the Galaxy made by Seares, Shapley, Plaskett, Oort and others so clearly indicate.

If our ideas of the nature of the universe are thus in a very early stage, the same may be said of our knowledge of the evolution of the stars. Recent discoveries in physics have greatly modified our conception of stellar evolution, affording a rational explanation of scores of questions formerly unanswered, but raising many new and fascinating problems. Giant stars with diameters several hundreds of times that of the sun, expanded by internal pressure to gossamer tenuity, lie near one end of our present stellar vista, with dwarfs of a density more than 50,000 times that of water near the other. The sun, a condensing dwarf, 1.4 times as dense as water, stands on the downward slope of stellar life. The continual radiation that marks the transition from giant to dwarf is now attributed to the transformation of stellar mass into radiant energy, thus harmonizing with Einstein's

views and accounting for the decrease in mass observed with advancing age. Surface temperatures ranging from about 1600° C. in the earlier stage of stellar life to 30,000° or more at its climax, and internal temperatures perhaps reaching 50,000,000° are among the incidents of stellar existence. But here again, while theory and observation have recently joined in painting a new and surprising picture of celestial progress, important differences of opinion still exist and many of these await a more powerful telescope to discriminate between them. For while theories based on modern physics have been our chief guide in recent years, the final test of all theories, as well as their essential source, is observation, and often our present instruments are insufficient to meet the demand.

So much in brief for the questions of celestial structure and evolution, though I have had to pass over the greatest of these problems: that of determining with certainty the successive stages in the development and motions of the spiral nebulæ, a phase of evolution vastly transcending that involved in the birth, life, and decline of a particular star. I may add only a word regarding the rôle of great telescopes in the study of the constitution of matter.

The range of mass, temperature, and density in the stars and nebulæ is of course incomparably greater than the physicist can match in the laboratory. It is, therefore, not surprising that some of the most fundamental problems of modern physics have been answered by an appeal to experiments performed for us

in these cosmic laboratories. For example, one of the most illuminating tests of the modern theory of the atom has recently been made at the California Institute by Bowen in a study of the characteristic spectrum of the nebulæ, where the extreme tenuity of the gas permits hydrogen and nitrogen to exist in a state harmonizing with theory but unapproachable in any vacuum-tube. Similarly, Adams' observations of the companion of Sirius with the Hooker telescope confirmed Eddington's prediction that matter can exist thousands of times denser than any terrestrial substance. In fact, things have reached such a point that a far-sighted industrial leader, whose success may depend in the long run on a complete knowledge of the nature of matter and its transformations, would hardly be willing to be limited by the feeble range of terrestrial furnaces. I can easily conceive of such a man adding a great telescope to the equipment of a laboratory for industrial research if the information he needed could not be obtained from existing observatories.

The development of new methods and instruments of research is one of the most effective means of advancing science. In hundreds of cases the utilization of some obvious principle, long known but completely neglected, has suddenly multiplied the possibilities of the investigator by opening new highways into previously inaccessible territory. The telescope, the microscope, and the spectroscope are perhaps the most striking illustrations of this fact, but new devices are constantly being found, and the result has been a com-

Fig. 9. Central part of the Great Nebula in Andromeda. (Duncan.)

plete transformation of the astronomical observatory.

From our present point of view the chief question is the bearing of these developments on the design of telescopes. To Galileo a telescope was a slender tube, 3 or 4 feet in length, with a convex lens at one end for an object glass, and a concave lens at the other for an eyepiece. With this "optic glass" the surprising discoveries described in the "Sidereus Nuncius" were made, which shifted the sun from its traditional position as a satellite of the earth to the centre of the solar system, and greatly enlarged the scale of the universe. From this beginning the refractor grew to the scale of the Lick and Yerkes telescopes.

Meanwhile it had become clear that the reflecting telescope possessed many advantages over the refractor. Chief among these are its power of concentrating light of all colors at the same focus and the fact that the light does not pass through the mirror, but is reflected from its concave front surface. Speculum metal, a highly polished alloy of tin and copper, was used for the early reflectors, reaching a maximum size in Lord Rosse's 6-foot telescope. Mirrors of glass, silvered on the front surface, were then introduced, and proved superior in lightness and reflecting power. Moreover, optical glass perfect enough for lenses cannot be obtained in very large sizes, and even if it could, the loss of light by absorption in transmission through the glass would prevent its use for objectives materially exceeding that of the Yerkes telescope. Therefore, our hopes for the future must lie in some form of reflector.

It is evident that a lens, through which the starlight passes to the eye, must be mounted in a very different way from a concave mirror, which receives the light on its surface and reflects it back to the focus. The large concave mirror lies at the bottom of the telescope tube, which is usually of light skeleton construction, open at the top. The surface of the mirror is figured to a paraboloidal form, which differs somewhat from a sphere in curvature, and has the power of concentrating the parallel rays from a star in a point at the focus. This focus is near the top of the tube, opposite the centre of the mirror.

For some classes of work it is desirable to place the photographic plate, small spectroscope, or other accessory instrument at this principal focus, centrally within the tube. Some starlight is thus cut off from the large mirror, but the loss is small and is less than with other arrangements. Newton interposed a plane mirror, fixed at an angle of 45°, which reflected the light to the side of the tube, where he placed the eyepiece. Cassegrain substituted a convex mirror for Newton's plane. Supported centrally at right angles to the beam, it changes the convergence of the rays and brings them to a focus near the large mirror. An inclined plane mirror may be used to intercept them, thus bringing the secondary focus at the side of the tube, or the large mirror may be pierced with a hole, allowing the rays to come to a focus close behind it.

In a third arrangement, the rays may be sent through the hollow polar axis of the telescope to a secondary focus at a fixed point in a constant tempera-

ture laboratory. This arrangement, first suggested by Ranyard, was embodied with both the Newtonian and Cassegrain methods in the mountings of the 60-inch and 100-inch telescopes of the Mount Wilson Observatory. By these means we may obtain any desired equivalent focal length (which varies with the curvature and position of the small convex mirrors) and thus photograph celestial objects on a large or small scale, as required by the problem in hand. Furthermore, we can use to the best advantage all types of spectroscope, photometer, interferometer, thermocouple, radiometer, photo-electric cell, and the many other accessories developed in recent years.

These accessory instruments and devices have made possible most of the discoveries of modern astrophysics. The stellar spectroscope, originally merely a small laboratory instrument attached to a telescope, has grown to the dimensions of the powerful fixed spectrograph of 6 inches aperture and 15 feet length, recently used with splendid success by Adams and others in photographing the spectra of some of the brightest stars. The development of this method of high dispersion stellar spectroscopy, initiated in the early days of the Yerkes Observatory, was one of my chief incentives in endeavoring to obtain large reflecting telescopes for the Mount Wilson Observatory. The recent advances in our knowledge of the atom and the consequent complete transformation of spectroscopy from an empirical to a rational basis greatly increase the possibilities of analyzing starlight. In most of the small-scale spectra photographed with or-

Fig. 10. Outer part of the Great Nebula in Andromeda, enlarged, resolved into stars by the 100-inch telescope. (Duncan.)

dinary stellar spectrographs the lines are so closely crowded together that they cannot be separately analyzed or measured. With a larger telescope we could push the dispersion to the point attained by Rowland in his classic studies of the solar spectrum, and thus take full advantage of the great possibilities of discovery offered us by recent advances in physics.

These details are important because they point directly to the type of telescope required. It is true that in some cases lenses may be used instead of convex mirrors for enlarging the image; but in our judgment the design should permit observations to be made in the principal focus of the large mirror, at a secondary focus just below the (pierced) mirror, and at another secondary focus in a fixed laboratory.

Telescope mountings for mirrors as large as 300 inches have been designed by Ritchey, Pease, Porter and others, and there would certainly be no difficulty in building a thoroughly satisfactory mounting for a 200-inch reflector. Of all the optical and mechanical problems involved only one presents real difficulties, but there is no reason to think that these cannot be surmounted. This is the manufacture of the disc for the large mirror.

Our chief problem in the case of the Hooker telescope was to obtain a suitable glass disc. The largest previously cast was that for the 60-inch mirror of our first large reflector. This is 8 inches thick and weighs a ton. The 100-inch disc, 13 inches thick, weighs nearly 5 tons. To make it three pots of glass were poured in quick succession into the mold. After a long

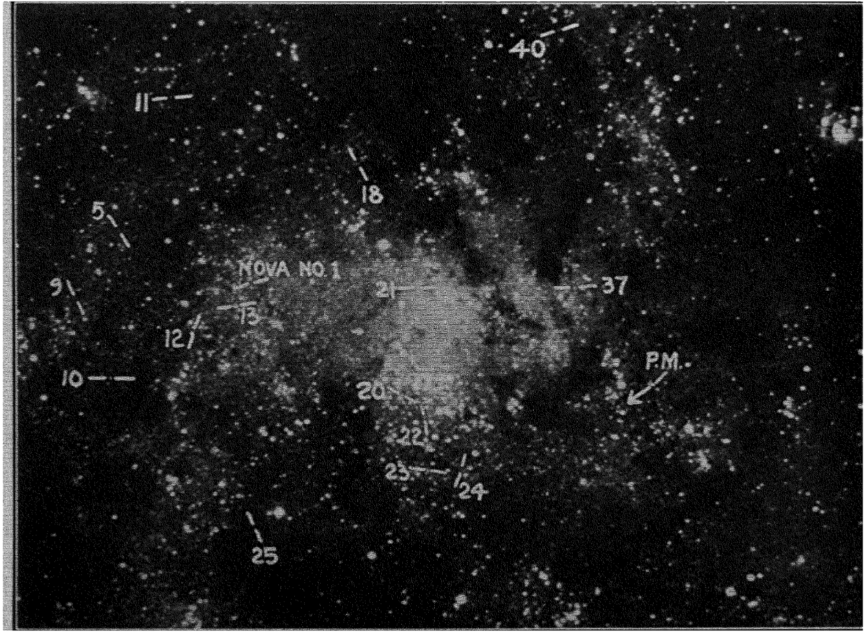

Fig. 11. Central part of the spiral nebula M 33 Triangulum, enlarged, showing variable stars discovered with the 100-inch telescope. (Hubble.)

annealing process, to prevent the internal strains that result from rapid cooling, the glass was delivered to us. Unlike the discs previously sent by the French makers, it contained sheets of bubbles, doubtless due in part to the use of the three pots of glass, while but one had sufficed before. Any considerable lack of homogeneity would result in unequal expansion or contraction under temperature changes, and experiments were, therefore, continued at the glass factory in the Forest of St. Gobain in the hope of producing a flawless disc. As they did not succeed, the disc containing the bubbles was given a spherical figure and tested optically under a wide range of temperature. Its performance convinced us that the disc could safely be given a paraboloidal figure for use in the telescope, where it has served admirably ever since for a great variety of visual and photographic observations.

Recently, important advances have been made in the art of glass manufacture, and mirror discs much larger and better than the 100-inch can now undoubtedly be cast. Pyrex glass, so useful in the kitchen and the chemical laboratory because it is not easily cracked by heat, is also very advantageous for telescope mirrors. Observations must always be made through the widely opened shutter of the dome, at temperatures as nearly as possible the same as that of the outer air. As the temperature rises or falls the mirror must respond. The small expansion or contraction of Pyrex glass means that mirrors made of it undergo less change of figure and, therefore, give more sharply defined star images—a vitally important matter in all classes of

work, especially in the study of the extremely faint stars in the spiral nebulæ.

Doctor Arthur L. Day of the Carnegie Institution of Washington, working in association with the Corning Glass Company, has succeeded in producing glass with a higher silica content than Pyrex and, therefore, with a lower coefficient of expansion. Moreover, Doctor Elihu Thomson of the General Electric Company had made* discs up to 12 inches in diameter of transparent fused quartz (pure silica), which is superior to all other substances for telescope mirrors. The chief difficulty in the manufacture of fused quartz has been the elimination of bubbles. These would do no harm whatever within a large telescope mirror, provided its upper surface were freed from them by a method used by Doctor Thomson. In fact, the presence of a great number of bubbles would be a distinct advantage in reducing the weight of the disc. As there is every reason to suppose that a suitable glass or quartz disc could be successfully made and annealed, and as the optical and engineering problems of figuring, mounting, and housing it present no serious difficulties, I believe that a 200-inch or possibly even a 300-inch telescope could now be built and used to the great advantage of astronomy.

*In 1927, when the article on which this chapter is based was written.

Chapter II

EXPLORING THE SOLAR ATMOSPHERE

As we have seen in the last chapter, many problems of astronomy demand large telescopes for their solution. But by carefully choosing his field, the observer with small instruments can make important contributions to knowledge. This is especially true in the case of the sun, the only one of all the stars near enough to show an appreciable disc. It goes without saying that this easily accessible star merits our special attention.

The atmosphere of the sun, previously seen only during total eclipses, has been partly accessible to daily observation during the last sixty years. Since the discovery of Janssen and Lockyer in 1868 our means of detecting the characteristics of its various levels have steadily improved, thus gradually disclosing many remarkable phenomena, which the powerful methods of modern physics are now beginning to interpret. Recently an instrument has been developed which opens new opportunities for research, not only on the nature of these phenomena but also regarding the probable relationship between solar outbursts and such terrestrial disturbances as auroras, magnetic storms, and variations in radio transmission. Two oscillating

slits, which transmit to the eye only the light of glowing hydrogen, render visible against the sun's surface the violent eruptions hitherto concealed by its overpowering glare. In order to appreciate the bearing of recent explorations of the solar atmosphere with this device, let us briefly recall some of the earlier work, beginning with the observation of two total eclipses.

TWO SOLAR ECLIPSES

On the 8th of July, 1842, a total eclipse of the sun attracted wide attention in Europe. The path of totality, where many astronomers were in waiting, extended across Italy and the south of France. On an upper floor of the University of Pavia Francis Baily, an English stock-broker distinguished as an amateur astronomer, had set up his telescope. Just as the last rays of the sun were cut off by the advancing moon he was "astounded by a tremendous burst of applause from the streets below, and at the same time was electrified at the sight of one of the most brilliant and splendid phenomena that can well be imagined. For at that instant the dark body of the moon was suddenly surrounded with a corona, or kind of bright glory similar in shape and relative magnitude to that which painters draw round the heads of saints. . . . But the most remarkable circumstance attending the phenomenon was the appearance of *three large protuberances* apparently emanating from the circumference of the moon. . . . They had the appearance of mountains of prodigious elevation; their color was red tinged with lilac or purple. . . . These three

protuberances were visible even to the last moment of total obscuration . . . and when the first ray of light was admitted from the sun they vanished altogether, with the corona, and daylight was instantaneously restored."

These enormous red prominences, estimated by Arago to be 54,000 miles high, had been seen in other forms and positions at previous eclipses, but their serious study, begun in 1842, did not lead to definite conclusions until 1868. In August of that year, while analyzing their light with a spectroscope at a total eclipse in India, the French astronomer Janssen detected the characteristic red and blue lines of hydrogen. These were very bright, and he exclaimed that he meant to see them again without waiting for another eclipse. The following morning, in full sunlight, he succeeded, and from that time to this the most spectacular of all solar phenomena have been open to daily observation.

The principle of the method, which reveals the chromosphere and prominences, but not the larger and fainter corona, is easily understood. We fail to see the red prominences against the sky merely because the intensely bright light of the sun, when scattered in our atmosphere, makes a glare so brilliant as to hide them completely. From a point outside the earth's atmosphere the sky around the sun would appear black, and both the corona and prominences would be clearly visible. We therefore need a means of diminishing the glare of the sky without reducing their brightness.

This means is afforded by the spectroscope, which spreads out and thus weakens the white light of the sky without greatly weakening the bright lines due to the glowing hydrogen and helium in the prominences. Thus these lines become visible, projecting beyond the edge of the sun against the faint rainbow background caused by the dispersed light of the sky (Fig. 12). Unfortunately, this method does not reveal the much fainter corona, which extends far beyond the red prominences into space. To photograph the corona we are still compelled to wait for the infrequent and very brief opportunities afforded by total eclipses of the sun. The prominences, however, may be easily seen on any clear day.

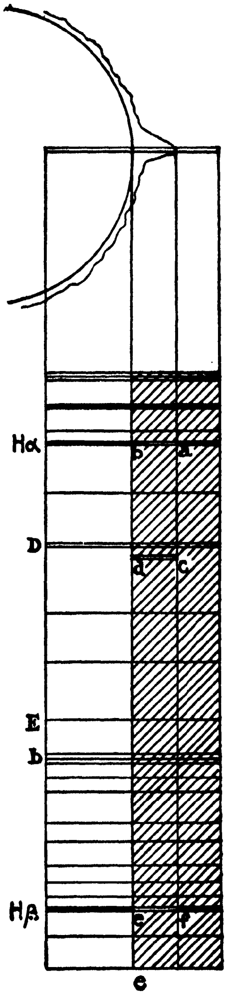

Fig. 12. Bright lines of hydrogen and helium in the spectrum of a prominence, observed in full sunlight with radial slit.

SOLAR PROMINENCES WITHOUT AN ECLIPSE

The bright hydrogen and helium lines seen by Janssen and Lockyer were merely images of the straight narrow slit of the spectroscope, and there-

fore did not show the forms of the prominences. However, by setting the slit across different parts of a prominence, its approximate form could be roughly determined by noting the varying length of the bright lines. This was the method used by

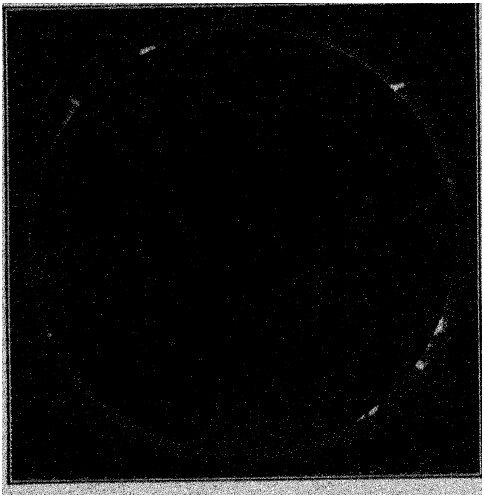

Fig. 13. Prominences photographed in full sunlight with the spectroheliograph.

the early observers until Zöllner and Huggins independently thought of widening the slit sufficiently to include an entire prominence, which could then be seen against the fainter background of the sky spectrum. Thus, in the daily visual records made by astronomers, the wide slit of the spectroscope is made tangent to the sun's image at many points around the circumference, and the forms of the prominences, as well as the continuous sea of hydrogen (chromosphere) from which

they rise, are sketched one by one into a complete cross-section of this portion of the solar atmosphere.

It is difficult to convey any conception of the brilliancy and fantastic beauty of the prominences as seen

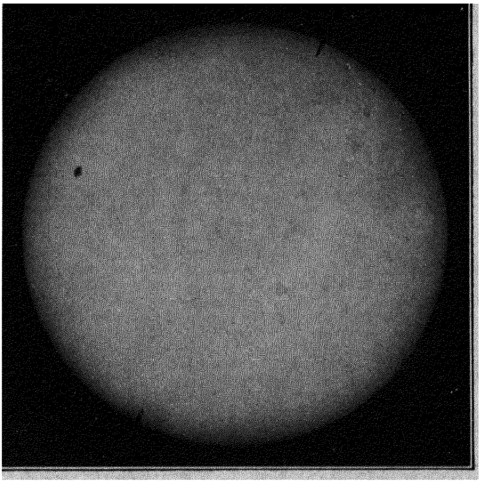

Fig. 14. Direct photograph of the sun, July 31, 1927. (Richardson.)

with the red hydrogen line. The greatest success has been achieved by Howard Russell Butler, of Princeton, whose admirable paintings of the corona and the prominences have been exhibited at the American Museum of Natural History in New York and the National Academy of Sciences in Washington. But as Secchi remarked many years ago in his book "Le Soleil," it is impossible to reproduce completely "the vivacity of color of these enormous masses, or to depict their rapid motions when they are shot by erup-

tions from the interior above the surface of the sun. The best drawings are inert and lifeless when compared with the actual phenomena. These incandescent masses are vivified by internal forces which seem to

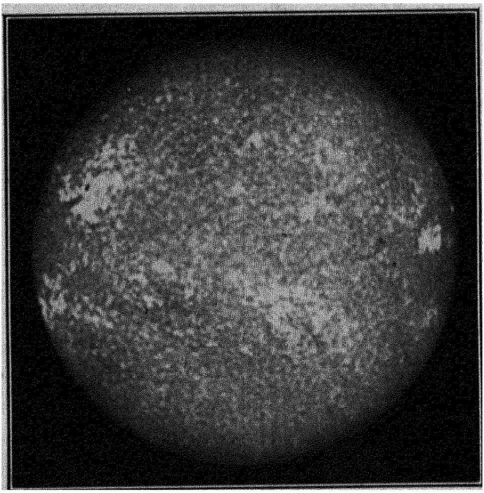

Fig. 15. Bright calcium flocculi, July 31, 1927. (Richardson.)

endow them with life; they glow with intense brilliancy, and their colors are so characteristic that they enable us to determine spectroscopically the chemical nature of their constituent gases."

The discovery of Lockyer and Janssen was followed by a period of great activity, in which English, French, Italian, German, and American astronomers joined in a general attack on the problems of the sun. Professor Charles A. Young, in whose memory a chair of astronomy has recently been endowed at

Princeton University, was one of the most active and successful of these pioneers in solar research. First at Dartmouth and later at Princeton he was the leader of the American astronomers who entered this novel

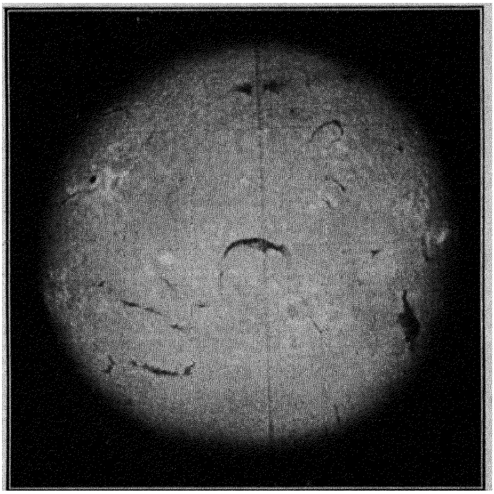

Fig. 16. Bright and dark hydrogen flocculi, July 31, 1927. (Richardson.)

and productive field of observation. I am indebted to him for my first view of the prominences, and for much encouragement and aid during the earlier period of my solar work. In the course of this chapter we shall have frequent occasion to refer to the results of his extensive studies.

The chromosphere, or continuous sea of glowing gas from which the prominences rise, is 5,000 or 6,000 miles in depth. The spectrum of its upper strata, like that of the quiescent prominences, is al-

ways marked by lines of hydrogen, helium, and calcium. At its base lies the "reversing layer," in which many metallic lines, frequently borne to higher levels by eruptive prominences, are also found. The height of the quiescent or slowly changing prominences often reaches 30,000 to 60,000 miles, while eruptive prominences, sometimes shooting outward at a rate of over 250 miles a second, have been seen to surpass elevation of 400,000 miles, or half the sun's diameter. Quiescent prominences are now considered to be supported in the solar atmosphere by the pressure due to the intense solar radiation, but it is still difficult to account completely for the great velocities and curious forms of the eruptions.

While the spectroscope thus reveals the form of the prominences that project beyond the limb against the sky, it can ordinarily be used only with a narrow slit for the study of the spectrum of these and other objects on the sun's disc. This is so much brighter than the sky that the wide-slit method fails to show the characteristic structure of the solar atmosphere against it, excepting the bare outline of occasional objects of unusual intensity. But fortunately this difficulty can be easily overcome.

Cut a slit about a hundredth of an inch wide in a piece of cardboard and hold it between the eye and an electric-lamp bulb. If the eye is not too near the slit, only a small part of the incandescent filament can be seen. Oscillate the slit and the entire filament becomes visible. To obtain a steady image, free from flicker, the slit should pass before the eye many times a second.

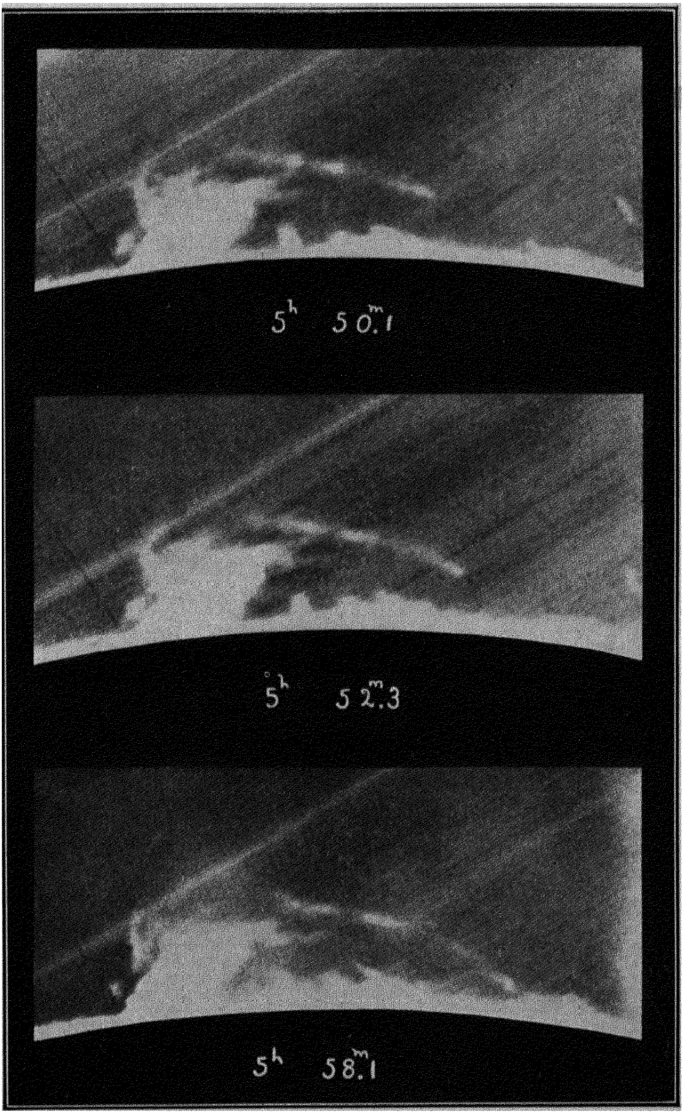

Fig. 17. Three photographs of a prominence, showing the motion of its tip toward a sun-spot in eight minutes. (Slocum.)

This simple principle can be used to render the forms of the prominences visible. What is needed is some device between the oscillating slit and the eye which will cut off all light except that due to hydrogen. The spectroscope is such a device, and some of the possibilities of this method were foreseen by Professor Young in 1870, when he attached to his spectroscope a pair of oscillating slits. With these he could see the forms of the prominences at the limb, but he was troubled by the vibration of his equatorial telescope due to the oscillation of the slits, and abandoned them when the wide-slit method was introduced. So far as I can learn, he did not try the oscillating slits for the detection of prominences on the disc, but in any case the dispersion of his spectroscope was insufficient for this purpose. Nevertheless, the credit for building the first spectrohelioscope (as I have named the instrument) and applying it to the observation of prominences at the limb belongs to Professor Young, who was also the first to photograph the forms of single prominences through an open slit.

THE GRADUAL DISCLOSURE OF THE SOLAR ATMOSPHERE

Much of our knowledge of the solar atmosphere has been derived from photographic observations, which have been in progress for many years. In order to understand the possibilities of visual work with the spectrohelioscope, a brief review of the results of photography is essential.

The principle of the spectroheliograph, which oc-

Fig. 18. Hydrogen flocculi photographed on three successive days, showing their changing forms and motion toward the limb due to the sun's rotation. (Joy.)

curred to me in 1889, does not differ greatly from that of Young's instrument with oscillating slits, and had indeed been suggested by other astronomers. It involves the use of a spectroscope with a fixed second slit, through which a single line (usually of calcium or hydrogen) is admitted to a photographic plate. The whole spectroscope is mounted on steel balls and moved slowly by a motor, so that the first slit crosses the solar image, which, like the photographic plate, remains at rest. Or the spectroscope may be fixed in position, and the solar image and plate moved across the first and second slits respectively. A monochromatic image of the sun is thus gradually built up on the plate from countless adjoining images of the narrow spectral line.

Professor Young had detected visually the two bright violet calcium lines H and K in the prominences, and these were used in 1891 with my first spectroheliograph at the Kenwood Observatory for the photography of prominences at the sun's limb (Figs. 13, 17, 18 and 38). Young had also found these lines to be bright on the disc in the neighborhood of sun-spots, and this important discovery opened the way into a new field of solar research. Early in 1892 an improved spectroheliograph was used at Kenwood for the photography of the forms of these areas, which turned out to be extensive clouds of brilliant calcium vapor, floating in the solar atmosphere above and near sun-spots and at many other places on the sun's disc (Fig. 15). These bright calcium clouds (called flocculi) are confined to levels within a few thousand

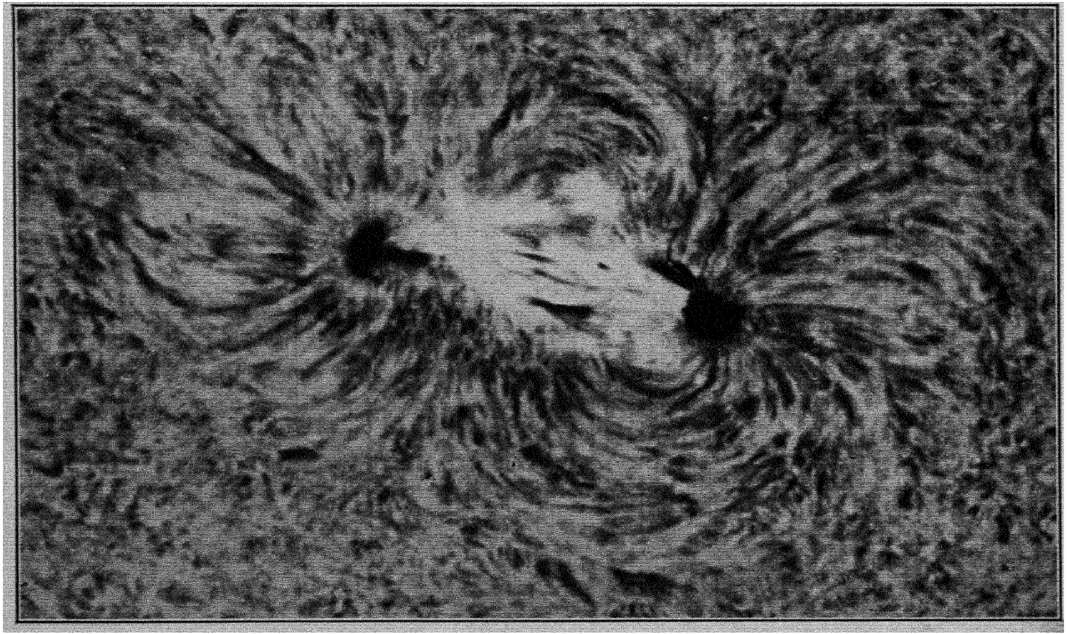

Fig. 19. Complex cyclonic structure of the hydrogen flocculi surrounding a large bipolar sun-spot. (Humason.)

miles of the sun's surface and thus differ from the much higher prominences, which still escaped us except at the limb.

About this time Deslandres introduced at the Paris Observatory his velocity spectrograph, which permits the motion in the line of sight of the calcium vapor at various levels to be measured on photographs of the H or K line in successive sections of the sun. Evershed soon constructed and systematically used a spectroheliograph in England, and in 1893 Deslandres also began work with a spectroheliograph, which he employed for photography with the calcium lines and with some of the narrower dark lines. In 1903 Ellerman and I discovered *dark* hydrogen and calcium flocculi on the sun's disc with the Rumford spectroheliograph attached to the 40-inch Yerkes telescope. The long dark flocculi shown on these plates, which proved to be prominences projected against the sun (Figs. 16 and 18), were subsequently called "filaments" by Deslandres, who has studied them extensively at Meudon with the spectroheliograph and velocity spectrograph.

Five years later, at Mount Wilson, with the aid of plates sensitized by Wallace's method for red light, we discovered large vortices or cyclonic storms in the solar atmosphere above sun-spots (Figs. 27 and 28). The red hydrogen line Hα, with which they were found, is much more effective than the blue and violet lines used in our earlier work for the study of the hydrogen flocculi. It represents a higher region in the solar atmosphere, where the characteristic vortex

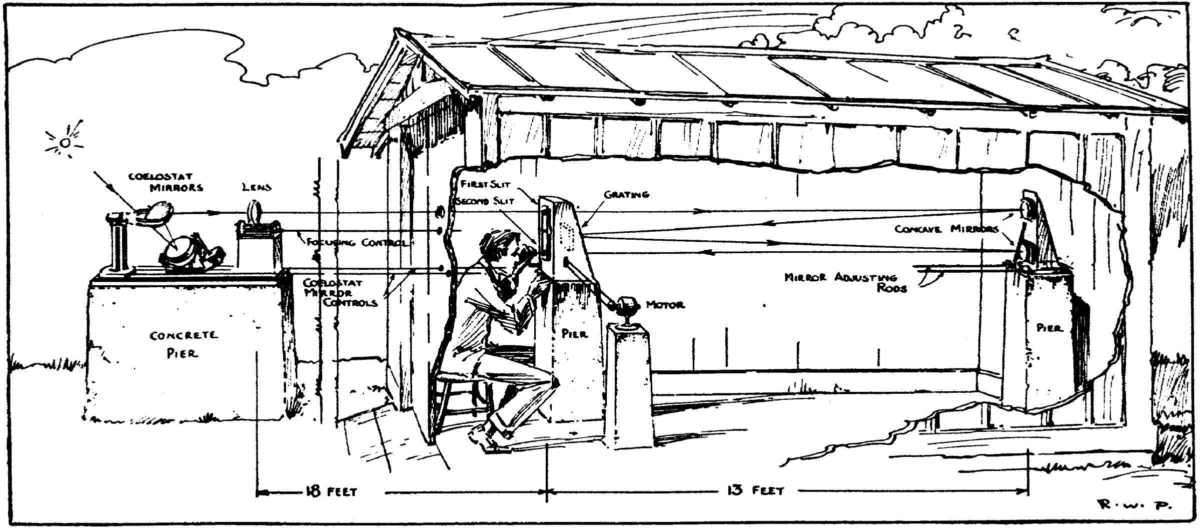

Fig. 20. General view of simple horizontal telescope and spectrohelioscope.

structure is most conspicuous. With a spectroheliograph of high dispersion, this line shows also the "alignments" discovered by Deslandres, which constitute a slender network of wide mesh associated with the filaments.

This brief and incomplete sketch may serve to show how some of the phenomena of the solar atmosphere have been successively brought within the range of the spectroheliograph. When examining photographs of the structure at different levels, it is important to recall that all of these phenomena overlie the white body of the sun, or photosphere, where the dark sun-spots, and the irregular bright faculæ that accompany them, are directly visible with any telescope (Fig. 14). The chromosphere, as we have seen, is thus a continuous sea of glowing gas several thousand miles deep, visible through the spectroscope in cross-section at the limb, with the prominences rising above it to altitudes often exceeding a hundred thousand miles. Against the disc its mottled structure can be photographed with the spectroheliograph, marked by extensive bright clouds of calcium flocculi, which occur chiefly within the zones parallel to the equator where sun-spots are also found. Rising to much greater elevations, and revealed in plan on spectroheliograms of the disc, are the hydrogen and calcium flocculi of the higher atmosphere, some of which may be seen with the spectroscope as prominences in elevation at the limb. The vortex structure of the hydrogen flocculi, resembling on a colossal scale the cyclonic storms and tornadoes in the earth's atmosphere, is one of the most striking fea-

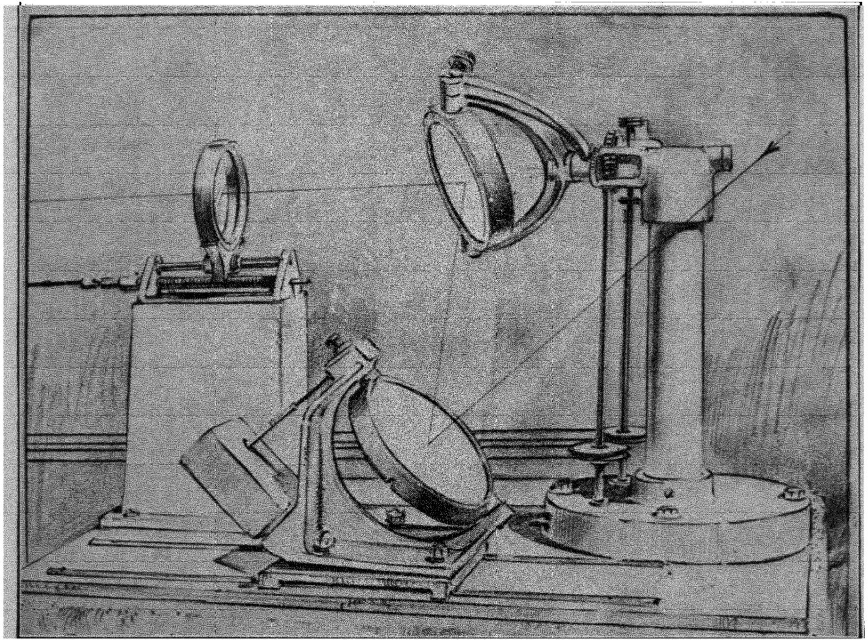

Fig. 21. Simple cœlostat telescope.

tures of these spectroheliograms (Figs. 28 and 29). Enveloping the whole, and reaching to heights of millions of miles, are the delicate streamers of the corona, seen only at total eclipses.

THE SPECTROHELIOSCOPE

With so much within the reach of the spectroscope and spectroheliograph, there might seem to be little room for another instrument of similar range. A very short experience with the spectrohelioscope, however, will suffice to convince one of its distinctive value. Objects familiar for years on hydrogen spectroheliograms suddenly seem to come to life, while difficulties in the interpretation of their complex structure are greatly reduced by its aid. If one is fortunate enough to see, as I did in Pasadena within a few days after my first spectrohelioscope had been adequately mounted, one of those violent outbursts on the sun's disc that are often followed on the earth by brilliant auroras and intense magnetic storms, the possibilities of the new instrument for a study of the relationship between solar and terrestrial phenomena will perhaps strike the observer most forcibly. Such possibilities have led me to design a complete solar telescope and spectrohelioscope of an inexpensive type, which can be built and used by professional or amateur astronomers and geophysicists and by radio students interested in the possible influence of solar eruptions on radio transmission.

The solar telescope comprises a small cœlostat, driven by a very inexpensive clock movement; an adjustable second mirror; and a single lens, which

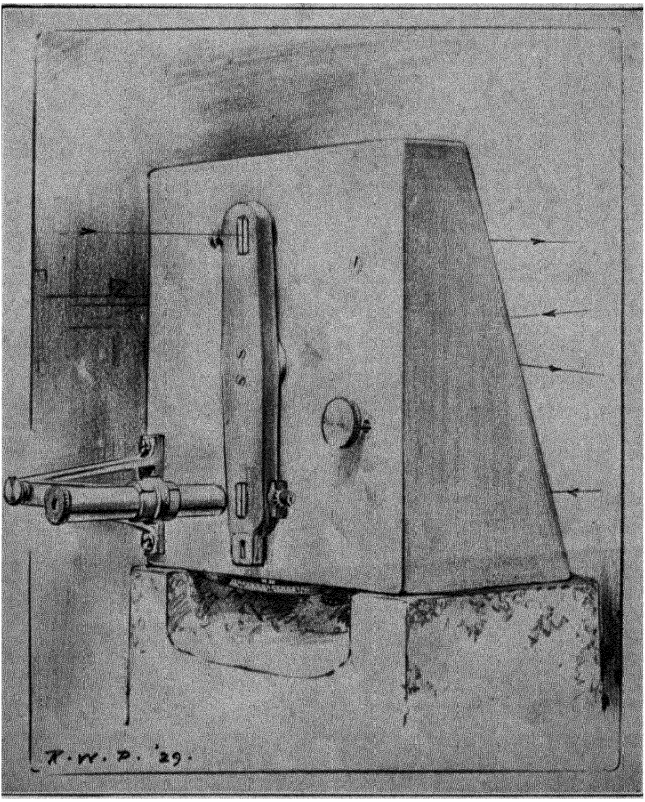

Fig. 22. Oscillating slits of spectrohelioscope.

forms a 2-inch solar image for observation by the spectrohelioscope. This consists of a simple spectroscope, provided with a pair of oscillating slits which exclude from the observer's eye all light except that of the red hydrogen line, and thus reveal the phenomena of the solar atmosphere.

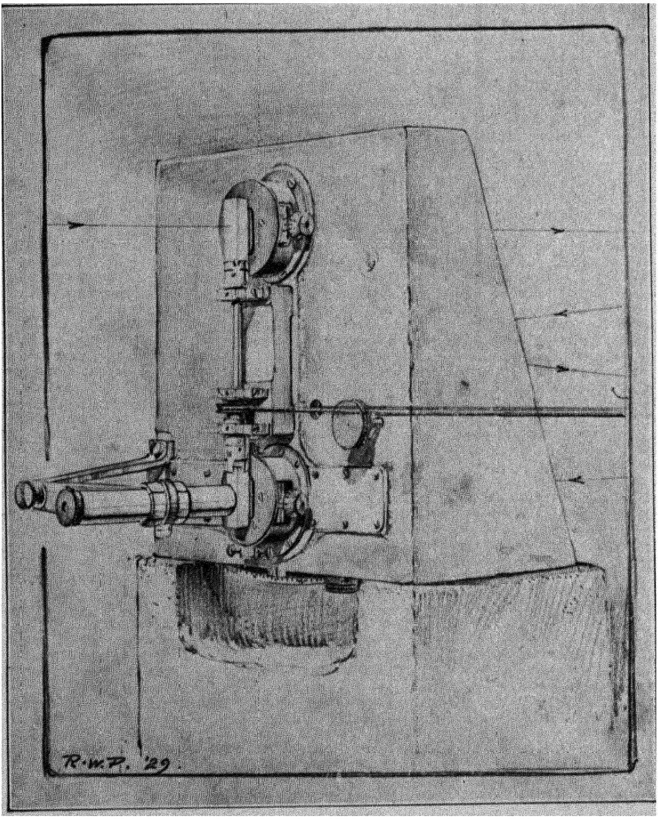

Fig. 23. Anderson rotating prisms as used with spectrohelioscope instead of oscillating slits.

SOLAR CYCLONES

Without dwelling on instrumental details, which are fully described elsewhere,* the use of the spectro-

*See Chapter III.

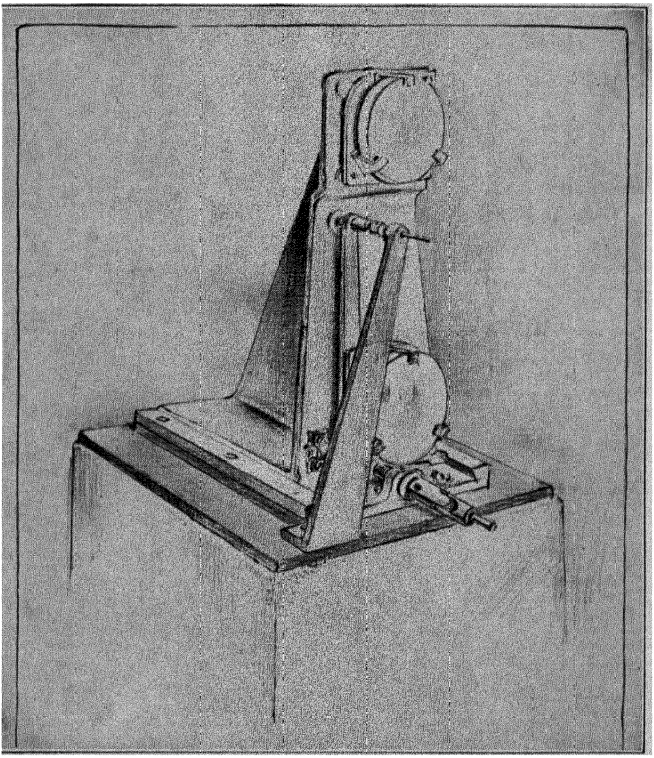

Fig. 24. Concave mirrors of spectroheliscope.

helioscope for the observation and analysis of the hydrogen flocculi and the measurement of their radial velocities may now be described.

As already remarked, this instrument shows that objects which appear as dark flocculi on the disc are often prominences which reach considerable heights when seen in elevation at the limb. Some quiescent

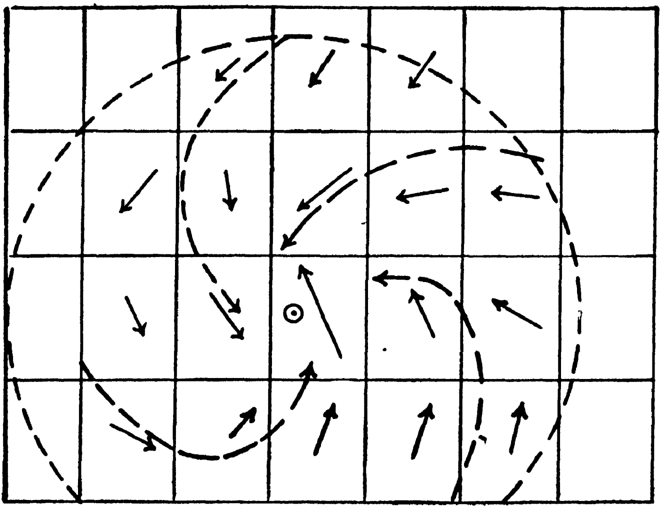

Fig. 25. Inward motion of low level winds and clouds in a terrestrial cyclonic storm. (Clayton.)

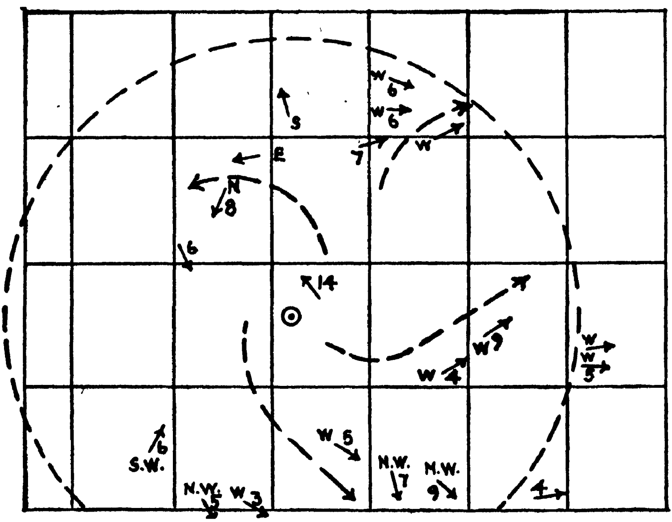

Fig. 26. Outward motion of high level clouds in a terrestrial cyclonic storm. (Clayton.)

prominences persist for weeks, and their varying forms on successive days, as they are carried toward the limb by the sun's axial rotation, are illustrated by Fig. 18.

The most interesting of the hydrogen flocculi, however, are those which assume cyclonic forms. The nature and cause of this beautiful structure are very difficult to determine, and in the study of this problem the spectroheliosсope has proved of the greatest service.

Imagine yourself fixed in space, with the earth rotating slowly beneath you. In the first few miles above its surface the presence of water vapor causes the formation of clouds when the air is chilled. These occur in various characteristic forms at different levels: I have seen as many as five distinct cloud strata at once after the breaking of a storm during the rainy season on Mount Wilson. From our imaginary observation-point in space an entire hemisphere of the earth is visible, so that the formation of a cyclonic storm, over an area averaging about a thousand miles in diameter, can be easily seen. These storms are marked by low barometric pressure near the centre, with surface winds blowing spirally inward, counter-clockwise in the northern and clockwise in the southern hemisphere. Sometimes the cyclonic motions are plainly marked by the structure of the clouds, which move spirally inward with the low-level winds near the surface (cumulus) and spirally outward at the higher level of the cirrus clouds (Figs. 25 and 26, as drawn by Clayton in the *Annals of the Harvard College Observatory*). When it is remembered that all differences of pressure in the earth's atmosphere dis-

appear at a height of about 12½ miles, it will be seen that the thickness of a cyclonic storm is very small in comparison with its area.

The simplest type of solar cyclonic storm, as it

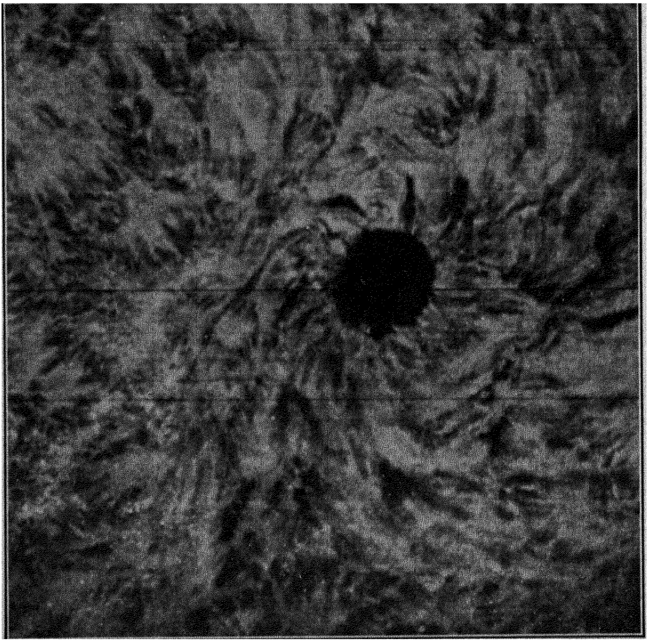

Fig. 27. Solar cyclone, showing spiral motion of hydrogen flocculi above a single sun-spot. (Ellerman.)

would appear in the spectroheliscope with the red hydrogen line, is illustrated in Fig. 27. Here we observe the hydrogen whirl above a single sun-spot in the southern hemisphere of the sun. I have frequently seen masses of hydrogen as large as the earth mov-

ing inward along such spiral paths at velocities exceeding 60 miles a second, the direction of the whirls (in about 80 per cent of the cases) corresponding to

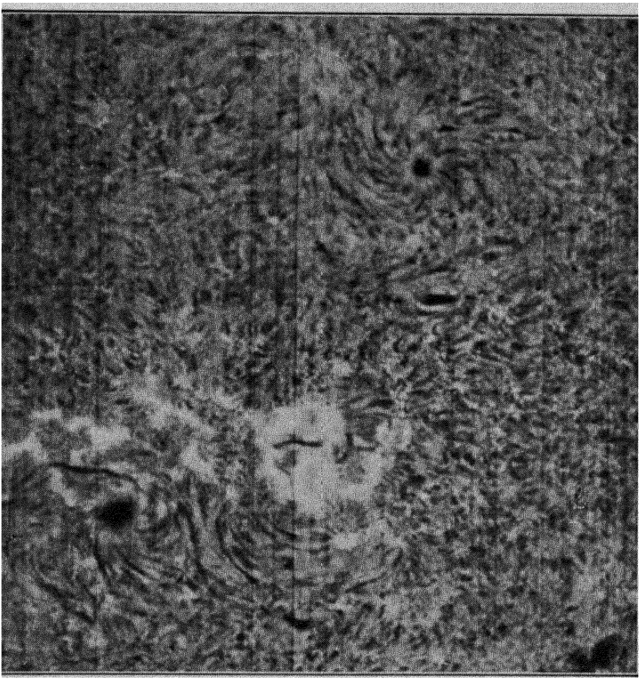

Fig. 28. Hydrogen whirls surrounding single spots in the northern and southern hemispheres, July 21, 1919. (Nicholson.)

that at low levels in terrestrial cyclones: counterclockwise in the northern and clockwise in the southern hemispheres (as in Fig. 27). The same effect, photographed in cross-section at the sun's limb by Slocum, is shown in Fig. 17, as I have repeatedly

observed it in prominences with the spectrohelioscope. To realize the violence of these solar storms, their great scale and the velocity of the inflowing gases must be remembered. Although we cannot see the lower part of the vortices, the spectroscopic measure-

Fig. 29. Hydrogen whirls surrounding the spots of the southern bipolar group of August 15, 1926. (Ellerman.) Both are clockwise and both showed inflow toward spots of opposite magnetic polarity.

ments of Evershed, St. John, and others indicate that the gases are not sucked down through the spots into the body of the sun, but flow nearly radially outward above the spots near the photosphere, after descending from the higher level of the inflowing hydrogen. The vortices thus resemble inverted terrestrial cyclones in their approximate form, though their real nature may be very different.

Look, for example, at the appearance of the hydrogen atmosphere above a bipolar sun-spot: a typical group of two spots having opposite magnetic fields

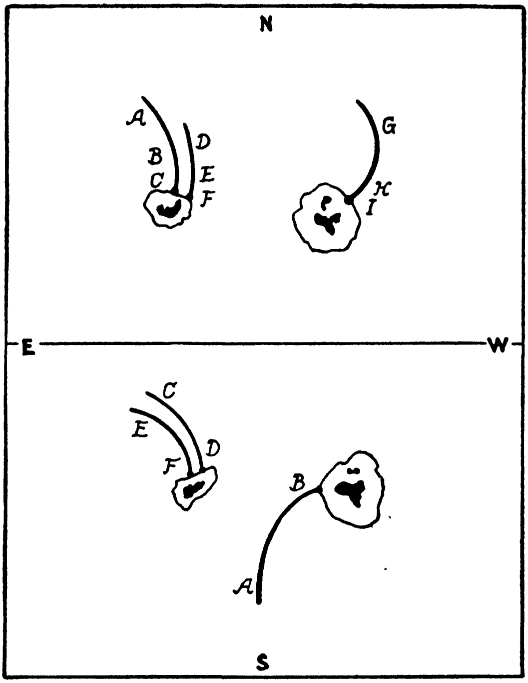

Fig. 30. Analysis of flocculi observed August 15 and 16, 1926, showing inflow of hydrogen toward spots of opposite polarity.

(Fig. 19). The lines of force in the solar atmosphere above such spots must be similar to those surrounding a bar magnet, and the structure of the hydrogen flocculi does bear a superficial resemblance to such a field. Nevertheless, an analysis of the flocculi which I have

recently made with the spectrohelioscope does not support the theory that ionized hydrogen is constrained by the magnetic fields to follow their lines of force.

On the contrary, I have found many direct contradictions of this theory. The spectrohelioscope shows that some of these curved flocculi represent arches of dark hydrogen seen in projection against the sun. These often rise, not from the sun-spots themselves, but from bright eruptive centres between two spots or at a distance from a single spot, then follow a curved trajectory resembling that of a projectile, and finally fall toward the surface at high velocity, sometimes descending toward a spot, sometimes at points where no spots are present. Moreover, on the electro-magnetic theory the direction of the hydrogen whirls around single spots, clockwise or counter-clockwise, should depend upon the magnetic polarity, positive or negative, of the spots, which does not prove to be the case. As already remarked, in about 80 per cent of the spots observed the direction of whirl corresponds with that of terrestrial cyclones.

Much research is still needed to explain the exact nature of solar cyclones and eruptions and of many other phenomena of the solar atmosphere. In this work the ability of the spectrohelioscope to show at a glance whether a particular mass of gas is moving toward or away from the observer and to give an instant measure of its velocity is one of its most valuable qualities. High radial velocity displaces the hydrogen lines—toward the violet if approaching, toward the red if receding. Thus a rapidly moving flocculus may

not be recorded at all on a photograph, because the hydrogen line at this point is thrown entirely outside of the second slit of the spectroheliograph. I have equipped the spectrohelioscope with a simple attachment called a "line-shifter," by which any part of the hydrogen line or its wings can be brought upon the second slit during observation. This is analogous to the tuning device on a radio set, with which any change of wave-length can be detected, compensated, and measured. The line-shifter permits a moving cloud of hydrogen to be picked up and brought to view, at the same time giving on a dial a measure of the change of wave-length and the consequent radial velocity of the gas. In this way the hydrogen arches have been analyzed and the rapid descent of hydrogen toward the surface observed and measured. Guided by a spectrohelioscope, and provided with a spectroheliograph similarly equipped with a line-shifter, the observer can now photograph flocculi previously lost at the most critical instants of rapid change, and thus complete the record and simplify the interpretation of these complex phenomena.*

*The spectrohelioscope can also be arranged for the photography of limited areas of the solar atmosphere, but the spectroheliograph, which easily covers large areas, is better adapted for photographic work.

*

Chapter III

SIGNALS FROM THE SUN

Brilliant outbursts on the sun have repeatedly heralded intense auroras and terrestrial magnetic storms. These are accompanied by earth currents that occasionally interrupt some forms of telegraph and cable service for hours, while radio transmission also appears to be adversely affected. There are thus many reasons for learning the true relationship between solar and terrestrial phenomena.

Professor Carl Störmer and his associates have studied the aurora for many years. At high-latitude stations in Norway they have taken countless photographs of its streamers, frequently in pairs, from the ends of a measured base line. The stereoscopic pictures thus obtained show the aurora hanging in space between the earth and the stars. Using the stars as points of reference, and measuring the displacement of sharp streamers from them, Störmer has determined the distance of the aurora from the earth (Fig. 33).

According to Störmer and others, the chief cause of the aurora should be sought in swarms of electrically charged particles, shot out from the sun and deflected by the lines of force of the earth. As every one knows, the earth is a great magnet, with its north

magnetic pole near Baffin's Bay and its south magnetic pole somewhere between Australia and the south pole of rotation. Therefore the aurora should be most

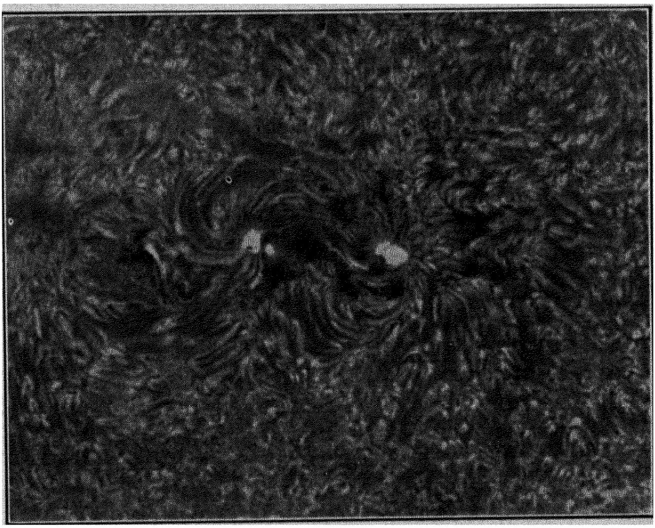

Fig. 31. Hydrogen flocculi (negative print) similar in structure to those in Figs. 29 and 30, surrounding the bipolar group of January 5, 1917. (R. Campbell.)

frequently and brilliantly seen near the regions where the lines of force of the terrestrial magnet converge toward its magnetic poles. In the far north Störmer has shown that the auroral rays descend to levels about 50 miles above the earth, while he has also found auroral curtains as high as 300 miles and diffuse auroras apparently extending up to about 600 miles, near the outermost limit of our atmosphere.

Readers of Sir Frank Smith's admirable address on theories of terrestrial magnetism* will recognize why no attempt is made to deal with this complex subject in the present volume. Gauss showed long ago

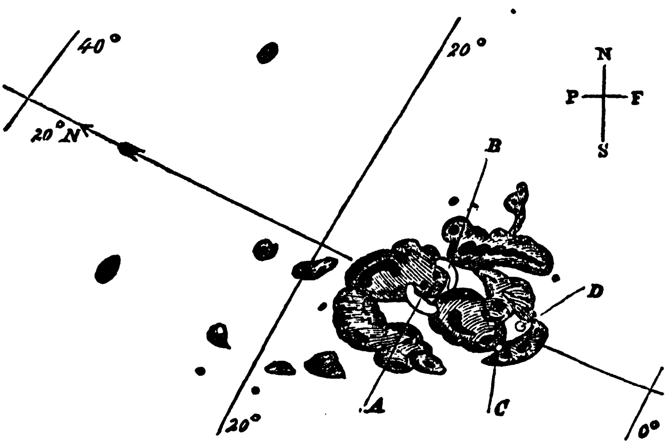

Fig. 32. Solar eruptions observed by Carrington, September 1, 1859. Note bright areas at A, B, C, D.

that the main origin of terrestrial magnetism is within the earth, while Schuster proved that the cause of its rapid variations must come from without. Its intensity is affected by changes in the sun's radiation, by the number of sun-spots and probably by other solar phenomena. The combined effects of these numerous causes are difficult to untangle, and it is always a wise policy not to attempt to describe several problems at

*Nature, September 13, 1930.

once but to fix our attention upon a single one, especially if we have a means of attacking it. For this reason the only question raised here is the probable source of those violent terrestrial disturbances which are shown both by brilliant auroras and exceptional magnetic storms. If this source lies in the sun, we want to know how it can be detected, what is its nature, and how soon its influence is felt across the gap of 93,000,000 miles between the sun and the earth.

In the last chapter I have mentioned the spectroheliosc ope, a new instrument for observing the sun in the light of a single element such as hydrogen. Shortly after the first spectrohelioscope had been mounted at my solar laboratory in Pasadena I received a letter from Professor Störmer which contained the following query:

"I have been most fascinated by a remarkable aurora here the 26th January of exceedingly *red* color, like the aurora in 1870. I should like to know from which active part of the sun this aurora was coming."

By a piece of rare good fortune I was able to answer this question with some chance of certainty. On January 24, 1926, while testing my spectrohelioscope (then in the experimental stage) between 11 h. 40 m. and 12 h. 15 m. Pacific Standard Time, I observed a bright eruption near a great sun-spot at about 22° north latitude, which was then close to the central meridian of the sun. Its form changed rapidly and in this and other respects it was evidently an exceptional object. On January 25 another eruption in the same region, the most brilliant and remarkable solar phe-

nomenon I have ever seen, continued throughout the morning and most of the afternoon. In view of the additional evidence given below, it is probable that this eruption marked the source of the discharge that produced both the brilliant aurora described by Störmer and the magnetic storm recorded on January 26 and 27 at Greenwich and elsewhere, notable as the most intense magnetic disturbance that had occurred for five years.

I naturally recalled the simultaneous observations in 1859 by Carrington and Hodgson of "two patches of intensely bright light" that suddenly broke out near the edges of a very large sun-spot, then close to the central meridian of the sun (Fig. 32). This brief apparition, unique in the history of solar research, was followed in about seventeen hours by a great magnetic storm and by a gorgeous aurora seen throughout Europe, America and Australia. The solar outburst was observed without spectroscopic aid and seems to have been of unparalleled intensity, apparently sending a shower of particles across to the earth at a velocity of about 1,500 miles per second.

It should be remembered that the solar image observed in 1926 was formed exclusively by the light of hydrogen, though the light of helium and of sodium also showed the brightest parts of the eruption. In other words, what I saw was not a temporary brightening of a portion of the direct solar image, such as Carrington observed, but of certain gases above the white photosphere in the sun's atmosphere. It thus resembled my first experience of this kind on July 15,

1892, when a similar outburst, also followed by a brilliant aurora and a violent magnetic storm on July 16, was photographed in several of its phases with the spectroheliograph of the Kenwood Observatory, Chicago, a few months after this instrument had been perfected and brought into daily use (Fig. 34).

As explained in the last chapter, the spectroheliograph, like the spectrohelioscope, produces a monochromatic image of the sun by the light of a single gaseous constituent of the solar atmosphere, in the Kenwood case calcium vapor. The Kenwood eruption occurred on a "bridge," a narrow dividing-line crossing a large sun-spot, which had appeared at the sun's eastern limb on July 7. On July 15 the spot, carried westward by the solar rotation, was near the central meridian of the sun. As usual, the dark spot was surrounded by glowing calcium, plainly shown in all the photographs of the series.

The first photograph, taken at 11 h. 8 m. (Chicago Mean Time), revealed nothing unusual, except that the "bridge" between the northern and southern parts of the spot was brighter than usual. Twelve minutes later a much brighter cloud of calcium vapor had appeared above the bridge. At its eastern end it turned sharply toward the north and terminated abruptly in a brilliant ball, overlying the northern part of the sun-spot. As the plates were not developed at once we knew nothing of the outburst and the next exposure was not made until 11 h. 47 m. The great eruption, which at that time completely hid the spot from view, extended also to the northwest, covering an area of

thousands of millions of square miles. An hour later the red hydrogen line was observed in the spot spectrum, and it was still found to be so bright that the form of the outburst could be well seen in hydrogen light (west of the spot) through the widely opened spectroscope slit. When the next photograph was taken the eruption had disappeared. As neither the form of the spot nor of the comparatively low calcium clouds surrounding it were changed by the disturbance, I believed it to represent an exceptionally brilliant eruption, at a higher level in the solar atmosphere. A violent magnetic storm, as recorded at the Stonyhurst College Observatory and elsewhere, began on July 16, reached an extreme intensity at 7 P. M. (Greenwich Mean Time) on that day, and continued until midnight of July 17. A very brilliant aurora was widely observed in the northern part of the United States the evening of July 16.

The eruption of January 25, 1926, was repeated in the same sun-spot group on February 22, after the expiration of a complete solar rotation had carried it around the sun and to a position 9° west of the central meridian. On this occasion the eruption was not seen visually, but fortunately it was photographed in both hydrogen and calcium light with the spectroheliograph of the Kodaikanal Observatory in India. Several stages of its development, described by Doctor Royds as without a parallel in the Kodaikanal records extending back to 1904, were shown by the photographs (Fig. 35).

These outbursts do not stand alone in the annals

Fig. 33. Stereoscopic photograph of the aurora of September 8, 1926. (Störmer.)

of astrophysics. Another similar eruption was the remarkable one of September 10, 1908, which lasted nearly four hours and extended across the solar equator, temporarily connecting two large spots in the northern and southern hemispheres. This was very completely recorded by Messrs. Fox and Abetti with the Rumford spectroheliograph of the Yerkes Observatory, and was followed after an interval of about twenty-six hours by an exceptional terrestrial magnetic storm (Fig. 36).

The most intense solar eruption ever detected at the Meudon Observatory (near Paris) was photographed by MM. d'Azambuja and Grenat with the red hydrogen line on October 13, 1926. Their most striking photograph probably represents this outburst near its maximum phase, as another taken 2 h. 10 m. earlier showed nothing exceptional, while one made 1 h. 6 m. later revealed only the outstanding parts of the gaseous mass, greatly reduced in brightness. It should be noted that the spot-group in which the eruption occurred was on the central meridian of the sun and that a violent magnetic storm took place about thirty-one hours after the solar display (Fig. 37). A bright aurora was seen almost simultaneously at Meudon.

In all of these instances, and in several others observed at Mount Wilson and elsewhere, an exceptionally bright eruption, occurring on or near the central meridian of the sun, was followed in from seventeen to thirty-six hours by an intense magnetic storm and a brilliant aurora. As the evidence favors the view that the electrified particles that gave rise to the au-

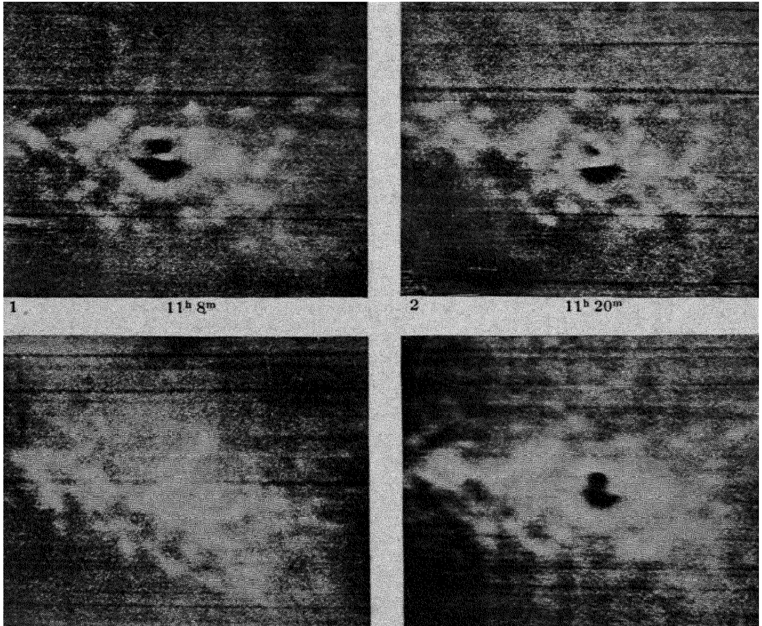

Fig. 34. Solar eruption of July 15, 1892, photographed with the Kenwood spectroheliograph.

roras and magnetic storms were shot from the sun by these eruptions, it is worth while to inquire a little more closely into their nature.

The great flames or prominences visible in the solar atmosphere are of two types, quiescent and eruptive. Quiescent prominences change slowly in form while the eruptive ones often develop suddenly and sometimes shoot to enormous heights at velocities exceeding 200 miles per second. Such prominences are chiefly composed of hydrogen, helium, and calcium, and the first question is whether their outflying atoms could actually reach the earth if fired radially from a point near the centre of the sun.

In order to escape from solar gravitational attraction an atom must move with a velocity of about 380 miles per second. The eruptive prominences do not seem to reach this velocity near the sun, where they sometimes rise to altitudes exceeding half the solar diameter before their expanding gases fade into invisibility. I have often watched their rapid ascent, as they appear in the red light of hydrogen with the spectrohelioscope. The heavens afford no phenomena more spectacular and I can strongly recommend such observations to amateur astronomers.

In an important paper "On the Possibility of the Emission of High-speed Atoms from the Sun and Stars," Milne has shown that just such effects as we apparently observe at their origin in the sun and later in the earth's atmosphere as auroral streamers can be accounted for by radiation pressure. Thirty years ago Nichols and Hull in America and Lebedew in Russia

independently succeeded in measuring in the laboratory the minute pressure of radiation produced by the most brilliant light-sources and Nichols suggested that the tails of comets, which develop as they approach the sun, might be accounted for in this way. Milne, as-

Fig. 35. Solar eruption of January 25, 1926, photographed with the spectroheliograph of the Kodaikanal Observatory. (Royds.)

suming a sudden increase in brightness at or near the sun's surface such as we often observe with the spectrohelioscope, proved that atoms of hydrogen or other gases exposed to its glare must move outward at higher and higher velocities. Soon the radiation pressure should exceed the backward pull of gravity and the expelled gases should fly into space with a velocity of some 1,600 kilometers (1,100 miles) per second. If aimed toward the earth, which may be the case if the

radiant source is near the centre of the sun, the flying gases, neutral or positively charged, should penetrate our atmosphere about twenty-six hours after their emergence from the sun. The positively charged atoms, including those of calcium observed in all solar prominences, should draw after them electrons, giving a cloud with a positively charged head and a negatively charged tail. From laboratory experiments Milne inferred that such a cloud would penetrate the rare upper gases of our atmosphere to a level of about 100 kilometers (60 miles), as observed by Störmer in the aurora. Moreover, Milne's theoretical velocity of transit between the sun and earth is in good agreement with the average interval of nearly twenty-six hours between the solar outburst and its terrestrial appearance. It thus seems probable that the solar eruptions described in this article were the direct sources of the subsequent auroras and magnetic storms.

The fact remains that many brilliant auroras and exceptional magnetic storms cannot be traced back to the sun. This may perhaps be due in some cases to the sudden development and short life of solar eruptions, which often cause them to be missed. The half-dozen spectroheliographs in regular use are not well distributed around the earth, and even in clear weather they are rarely employed to make more than a few photographs daily of the solar atmosphere. Fortunately they will soon be supplemented by a large number of spectrohelioscopes, several of which are already in operation.

When I found in 1926 that a powerful spectro-

helioscope could be effectively used with a small telescope, I designed an outfit which has been adopted by 25 observatories fairly well distributed around the earth. As the spectrohelioscope is 13 feet in length, it must usually be fixed in position, and therefore cannot be employed with small telescopes of the ordinary type, in which the lens and tube are moved by clockwork so as to follow celestial objects across the heavens. In the chosen design the telescope consists merely of a fixed single lens 4 inches in diameter and of 18 feet focal length, with a screw to focus the 2-inch solar image on the slit of the spectrohelioscope. No tube is needed between lens and slit, except for a short distance within the darkened spectrohelioscope house, where it serves to shield the observer's eyes from the sun's glare. A cheap plano-convex lens suffices instead of an achromatic one, because the image seen through the spectrohelioscope is formed by the monochromatic light of the red hydrogen line.

To supply the lens with sunlight, two small silvered plane mirrors are used. One of these (that of the cœlostat) is mounted at an angle equal to the latitude of the site and rotated at a uniform rate by an ordinary (two-dollar) clock movement. The cœlostat can be shifted from north to south, as the sun slowly changes its altitude from summer to winter, so as to reflect the fixed beam of parallel rays to a second plane mirror, which in its turn directs it to the lens that focusses the rays on the slit (Fig. 21). The solar image is held stationary by the driving-clock, but two slow-motion rods or cords connected with the

second mirror enable the observer to change its position, so as to bring any part of the sun's disc or the region surrounding it into the field of view.

Fig. 36. Solar eruption of September 10, 1908, photographed at the Yerkes Observatory. (Fox and Abetti.)

As for the spectrohelioscope itself, a detailed description is unnecessary.* In one of its forms it comprises a vertical oscillating bar, carrying two vertical slits near its extremities (Fig. 22). The white light

*See "The Spectrohelioscope and Its Work," *Astrophysical Journal,* December, 1929, March, 1930, and June, 1931.

from a portion of the solar image given by the cœlostat and lens passes through the upper slit, diverges to fill a 3-inch concave mirror 13 feet away, and is returned as a parallel beam to the optically plane surface of a diffraction grating, a highly polished plate of speculum metal, on which about 50,000 lines are accurately ruled at the rate of nearly 15,000 per inch. This grating forms a series of spectra, the brightest of which is directed to a second 3-inch concave mirror, mounted below the first one (Fig. 24). The focus of this mirror is on the lower oscillating slit, where an image of the red hydrogen line (H*a*) is formed. The adjustments are such that when the first slit moves to the right the hydrogen line moves to the left at exactly the same rate as the second slit, through which the observer looks with an eyepiece of low power. As the slits are oscillated rapidly back and forth by a small electric motor, the result is to exclude from the eye all light except that of the red line of hydrogen, which produces a persistent image of a part of the solar atmosphere. Thus hydrogen flames extending beyond the sun's edge or projected against the brilliant disc as bright or dark flocculi, quiescent or eruptive, can be perfectly seen.

An attachment for shifting the position of the hydrogen line with reference to the slit during observation permits the motions of the gas toward or from the earth to be instantly detected and measured. For this reason the rapidly changing phenomena of solar eruptions can be more effectively analyzed with the spectrohelioscope than with the spectroheliograph. As

an accurate recording instrument, however, the latter instrument remains unrivalled, in spite of its slower action. In my solar laboratory in Pasadena both instruments are used in conjunction with a powerful spectroscope, which is necessary for the visual or photographic study of magnetic fields in sun-spots and the general magnetic field of the sun. Another excellent form of spectrohelioscope has fixed instead of oscillating slits, with a pair of prisms, square in cross-section, revolving before them (Fig. 23). This ingenious device of Anderson's is generally preferable to oscillating slits.

It is easy to imagine a chain of spectrohelioscopes in use. At any particular observatory the sun may not be visible when an important eruption begins, either because of clouds or because it occurs after sunset, which comes early in the winter at high northern latitudes. Moreover, the observer usually has other duties and cannot be always on the watch. A co-operative plan, in which many instruments are employed, is therefore essential.

Suppose the observer at Greenwich, where one of our standard outfits is mounted, notices the beginning of an eruption not long before sunset on a winter's afternoon. Night may have fallen at stations to the east, while to the west the Atlantic imposes a wide barrier. In the United States, however, the sun stands high in the heavens, and unless cloudy weather prevents, the phenomenon may be followed by one or more of the dozen spectrohelioscopes between Boston and Pasadena. Then comes another break, but

this is already partly bridged by spectrohelioscopes in Samoa, New Zealand and Australia. An outfit recently tested by us for the Pasadena manufacturers has been sent to the National Institute of Astronomy at

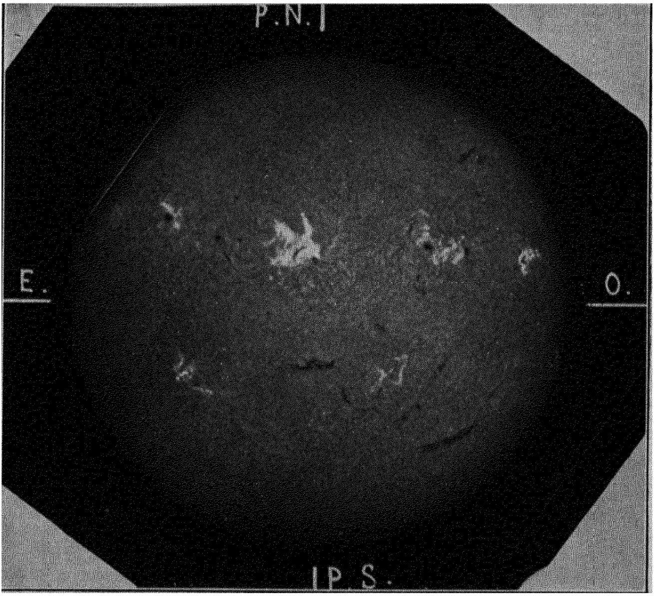

Fig. 37. Solar eruption of October 13, 1926, photographed at the Meudon Observatory. (d'Azambuja and Grenat.)

Nanking, China. The spectroheliograph at the Kodaikanal Observatory in India will soon be supplemented by a spectrohelioscope, and two of these instruments will probably be built and used by Indian astronomers in Madras. Beyond them are already mounted the spectrohelioscopes at Beirut, Syria, and at

the Arcetri Observatory overlooking Florence. Another has been ordered for use at the Observatory of the Polytechnic School in Zürich, and two or three others will soon be erected in England. In spite of clouds, if these instruments can be used in co-operation, and supplemented by additional outfits in the hands of astronomers at such intermediate longitudes as Brazil, Hawaii, Persia and Greece, few important solar outbursts should be missed.

Excepting the grating, for which no completely satisfactory substitute has yet been found, cœlostat telescopes and spectrohelioscopes like those mounted at the widely distributed stations just mentioned can be constructed by amateurs. Chiefly through the initiative and enthusiasm of Russell W. Porter, now of the California Institute of Technology, and Albert G. Ingalls, astronomical editor of *The Scientific American*, hundreds of American amateurs have built equatorial reflecting telescopes during the last few years. Most of these are of much larger aperture than the cœlostat telescope required for the spectrohelioscope, but they are not suitable in design for use with this instrument. I therefore hope that some of these amateurs will also decide to build cœlostat telescopes and spectrohelioscopes, and join in our co-operative project, which offers so many opportunities for new and attractive work. For those who prefer still simpler instruments I have designed a smaller cœlostat telescope and a single prism spectroheliograph, which can be easily built without the aid of machine tools, at very little expense and will photograph with calcium light

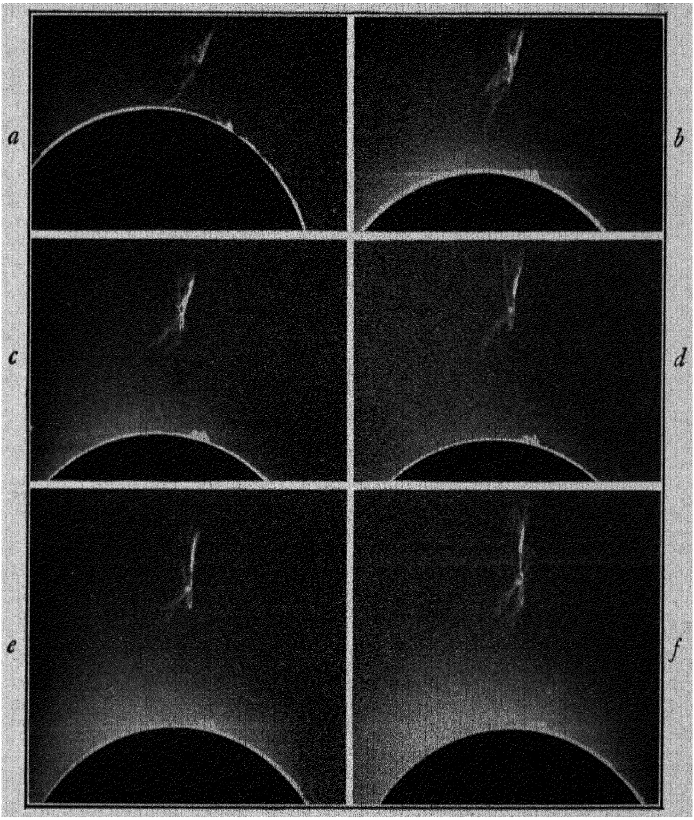

Fig. 38. Eruptive prominence photographed at the Kodaikanal Observatory, November 19, 1928: *a*, 7 h. 52 m.; *b*, 8 h. 35 m.; *c*, 8 h. 45 m.; *d*, 8 h. 52 m.; *e*, 8 h. 58 m.; *f*, 9 h. 3 m., I. S. T. Outward velocity 60 to 70 km. sec. in lower parts of prominence, 100 to 170 km. sec. in highest parts. Velocity increased with time, reaching 229 km. sec. at top between *e* and *f*. Height in *f* 495,000 miles; cut off by clouds at maximum height of 567,000 miles. (Royds.)

eruptions on the sun's disc like those described in this article.* In spite of its small dimensions and easy construction, this outfit will thus serve for new work of investigation, valuable from several points of view.

In the account of his classic observation of 1859 and the accompanying magnetic storm Carrington prudently remarked that "one swallow does not make a summer." It is natural to ask, even after examining the striking coincidences mentioned in this paper, whether a dozen swallows will suffice. Any one who has observed eruptive prominences at the sun's circumference can understand why some of them, wherever situated on the disc, might never hit the earth. Active sun-spots are often surrounded by eruptive regions, which shoot out rocket-like jets from time to time. These brilliant jets, which make various angles with the surface, usually describe curved arcs and fall back upon the sun, though some of them may perhaps escape. Eruptions of another class may have a better chance. These seem to rise nearly vertically, and if one occurred at a favorable point on the disc, and attained such a velocity as Milne has computed, some of its gases might reach the earth (Fig. 38). However, the horizontal acceleration discussed by Pike, which may result in a rapid dispersal of upward-moving clouds, must not be overlooked. Moreover, the fact that violent magnetic storms sometimes take place when no prior indication of such an event is afforded by any available solar observations, lends further zest to the problem.

*See *Scientific American*, October, 1931.

Whatever doubts may still exist, there can be no question as to the reality of a close relationship between certain solar and terrestrial phenomena. Although the electromagnetic influence of the magnetic fields always found in sun-spots cannot reach the earth, it has been known for half a century that the average intensity of the earth's magnetism fluctuates in close correspondence with the average number of sun-spots. It is also true that when a very large spot is near the centre of the sun there is likely to be an intense terrestrial magnetic storm, but equally large spots occasionally cross the disc without producing any such effect. The activity of a spot, usually accompanied by rapid changes in size or form, is an important test of its influence, and this activity is often indicated by eruptions of the type described in this chapter. Observations of the hydrogen or calcium atmosphere about active sun-spots, or in other disturbed regions of the sun, are therefore among our most promising means of revealing the probable source of auroras and magnetic storms. But our limited knowledge of the cause of solar eruptions, the persistence of a feeble aurora visible spectroscopically at all times, and the recurrence of magnetic storms at twenty-seven-day intervals, even after the disappearance of the large spots that may have marked their first outbreak, indicate the need of further investigations, in which amateur observers may play an active part.

Chapter IV

BUILDING THE 200-INCH TELE-SCOPE

Astronomers, like other men, spend most of their lives in hard and often tedious routine work. They are, however, sometimes fortunate enough to take part in a great adventure, and it is of such an adventure that I am now writing.

The pupil of the human eye—about a fifth of an inch in diameter—receives only a minute fraction of the light falling from a star upon the earth's surface. Imagine this pupil enlarged to a diameter of 9 feet, and endowed both with magnifying power and with the cumulative capacity of the photographic plate, which forms a visible image by adding up during long exposures the invisible rays of feeble celestial objects. Like our largest existing telescope, it could then penetrate millions of light-years into space and reveal about 1,500 million stars in our own galactic system and hundreds of thousands of "island universes" beyond the Milky Way.

In 1928 I described in *Harper's Magazine* some of the possibilities of still larger instruments.* A few months later, through the generosity of the International Education Board, funds were given to the California Institute of Technology in Pasadena for the

*Most of this article is embodied in Chapter I.

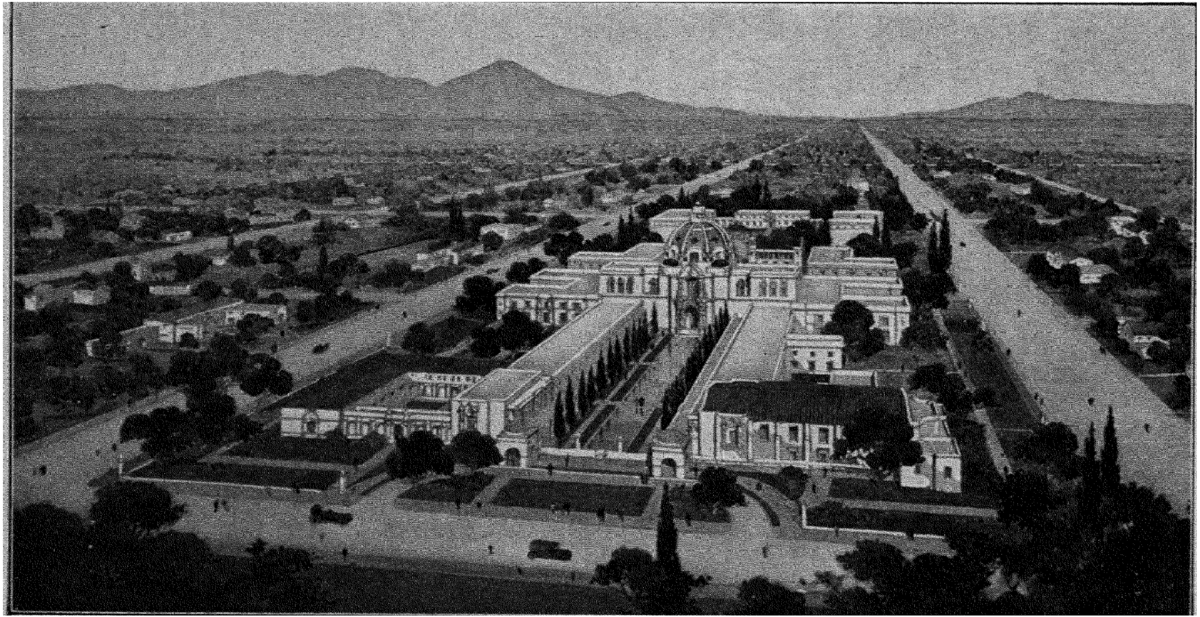

Fig. 39. Bertram Goodhue's original design for the California Institute of Technology, Pasadena.

construction of an Astrophysical Observatory and Laboratory, to be conducted in close co-operation with the Mount Wilson Observatory of the Carnegie Institution of Washington. This Observatory, which will be designed so as to supplement, not to duplicate, the Mount Wilson Observatory, is to be equipped with a 200-inch reflecting telescope and powerful auxiliary apparatus. It is our hope that the new telescope will be fully 10 times as powerful as the 100-inch Mount Wilson reflector, penetrate more than three times as far into space, and thus open for investigation an unexplored sphere of about 30 times the volume of that which has been hitherto sounded. Perhaps, however, the most important use of the new instrument and its accessories will be in the more intensive investigation of objects already known but inadequately studied because of our present optical limitations.

Astronomical observatories are not all alike. On the contrary, they show a greater diversity of design than the laboratories used in any other branch of science. The number of celestial objects is so great that a lifetime can be spent in measuring the "absolute" positions, the relative positions, or the speeds of small fractions of their number. Consequently, observatories are often erected for such special purposes, so that their sole equipment may consist of a meridian circle and astronomical clocks, or a photographic refracting telescope and machines for measuring the relative positions of stellar images, or a telescope and spectrograph for determining stellar motions. The results thus obtained are indispensable to astronomy, which

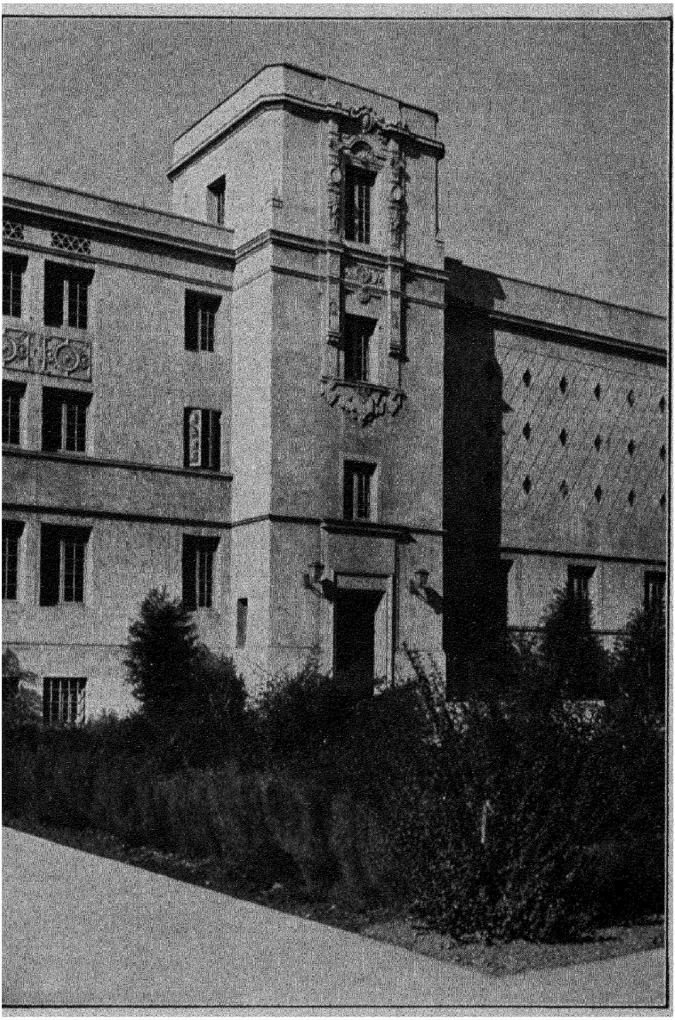

Fig. 40. The Norman Bridge Laboratory of Physics, California Institute of Technology.

through the ages has been fortunate enough to possess men of the skill and devotion required to accomplish these endless tasks of routine observation and measurement. The true value of their results often does not appear until long after their death, as in the discovery of the precession of the equinoxes more than two thousand years ago. The importance of Tycho Brahe's observations, which were bequeathed to Kepler, was brought out by Kepler's discovery of the laws of planetary motion that bear his name.

In recent years, however, the rapidly expanding scope of astrophysical research has revolutionized the observatory and multiplied its possibilities to the astronomer, the physicist, and the chemist. As the key to cosmic laboratories, which afford temperatures, pressures, densities, and masses greatly exceeding those attainable on earth, the telescope with its many auxiliaries has become as indispensable to the physicist and chemist as to the student of stellar evolution and the structure of the universe. For this reason a co-operative investigation of the physical, chemical, and astronomical aspects of the nature and properties of matter under the widest range of conditions was undertaken several years ago by the California Institute and the neighboring Mount Wilson Observatory. The resulting series of fundamental discoveries, both celestial and terrestrial, has now led to the provision for the 200-inch telescope and its accessories as a new and powerful means of extending them.

The method of organizing the new Astrophysical Observatory and its indispensable Laboratory is thus

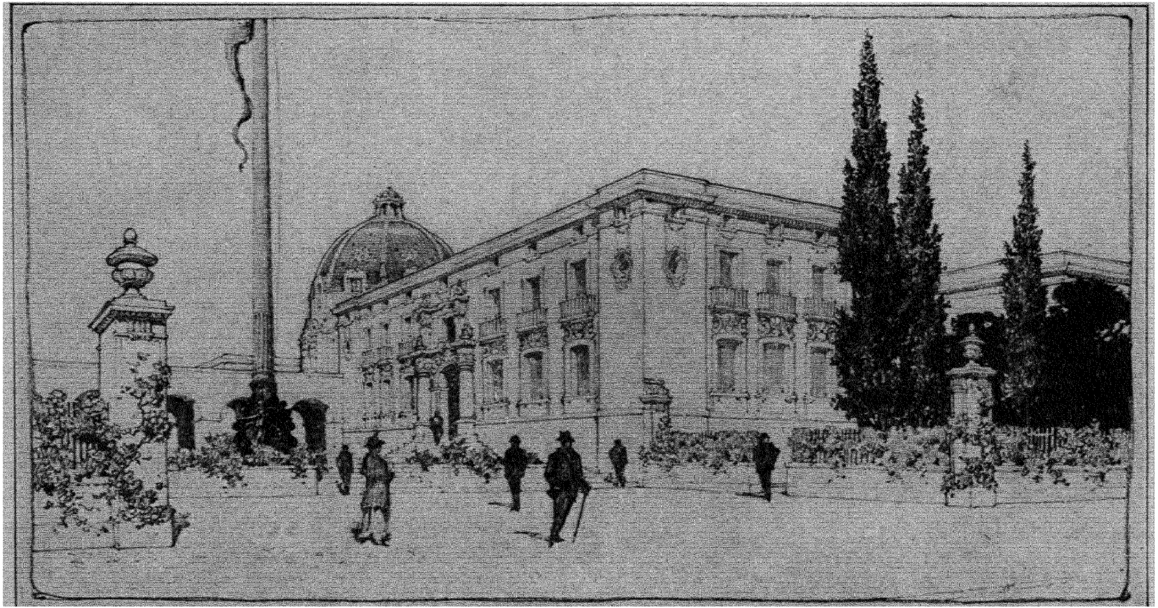

Fig. 41. The Gates Laboratory of Chemistry, California Institute of Technology, from a sketch by the architect.

plainly indicated. The optical and mechanical parts of the 200-inch telescope, naturally of the highest attainable perfection, should be mounted equatorially so as to command the heavens from the north pole to a region far south of the equator. It should be established at a site out of the path of frequent storms, where a great preponderance of clear weather is associated with the sharpest and steadiest telescopic images. It should be quickly adaptable for a wide variety of researches and provided with the best attainable means of recording and measuring celestial objects. It should have the immense advantage of the best laboratory facilities for interpreting its observational results. Its equipment should not be fixed once for all, but should constantly be extended and improved in pace with advances in physics, chemistry, and engineering. Finally, and most important of all, the new telescope should be used in close conjunction with all the present facilities of the Mount Wilson Observatory and those of the Norman Bridge Laboratory of Physics, the Gates Laboratory of Chemistry, and other branches of the California Institute, by the most competent group of investigators that can be recruited from these and other institutions in this country and abroad.

THE 200-INCH TELESCOPE

The designing of the telescope includes both optical and engineering problems, the first and most vital of which is that of obtaining a suitable mirror disc. Readers of this volume are aware that the images of

stars or other celestial objects are produced in reflecting telescopes not with the customary transparent lens of the more familiar refracting telescope, field-glass, or camera, but with a concave mirror, which lies at the bottom of the telescope tube, and converges back to a focus the parallel rays of starlight that fall on its polished upper face. This face, which must be highly reflecting, is ground and figured to a paraboloidal form, the curvature required to concentrate parallel rays in a point. The focus, therefore, as explained in Chapter I, is in the centre of the tube near the upper end, where the photographic plate or other recording device may be placed. By means of supplementary mirrors, plane or concave, the image may instead be formed at the side of the tube near its upper end, or at the bottom (where it is observed through a central hole in the large mirror), or in a laboratory below the hollow polar axis, where instruments such as long-focus spectrographs, requiring great stability, may be rigidly fixed in a constant-temperature laboratory.

The problem of producing large mirror discs, free from distortions caused by temperature changes in thick masses of ordinary glass, is of great importance, not merely to this particular project but equally so to all future plans for great telescopes.

Fused quartz (pure silica) is universally regarded by astronomers as the best possible material, because it is not appreciably affected by temperature variations. Doctor Elihu Thomson and his associate, Mr. A. L. Ellis, had already solved at West Lynn, Massachu-

setts, many of the extremely difficult technical problems involved in the use of fused quartz, and our first step was, therefore, to secure their co-operation and that of the General Electric Company. President Gerard Swope immediately agreed to have the work done in the Thomson Research Laboratory at actual cost, with no charge for commercial or administrative expenses. Several 22-inch discs, which met the most extreme optical tests, were soon produced, and a 60-inch is now in process of manufacture. A special method has been developed for this purpose. Selected crystalline quartz, in particles of a certain size, is heated to a high temperature to remove adherent air and then sprayed into an electric furnace through a peculiar form of multiple oxy-hydrogen burner. Fusion occurs at the face of the disc, where a temperature high enough to melt platinum is attained. Because of the remarkable properties of quartz a large disc thus built up was successfully cooled in twelve days, whereas a plate-glass disc of equal size would require many months to cool safely (Fig. 42). Some conception of the magnitude and difficulty of the ultimate task may be gained when it is stated that the fundamental problem is to construct a rigid concave mirror nearly 17 feet in diameter (200 inches), many tons in weight, whose surface is parabolically curved with an error less than two millionths of an inch.

To give an idea of the scale of the new instrument, it may be compared with the 100-inch Hooker telescope, now the most powerful in use. The Hooker mirror is about 13 inches thick, and weighs about 4½

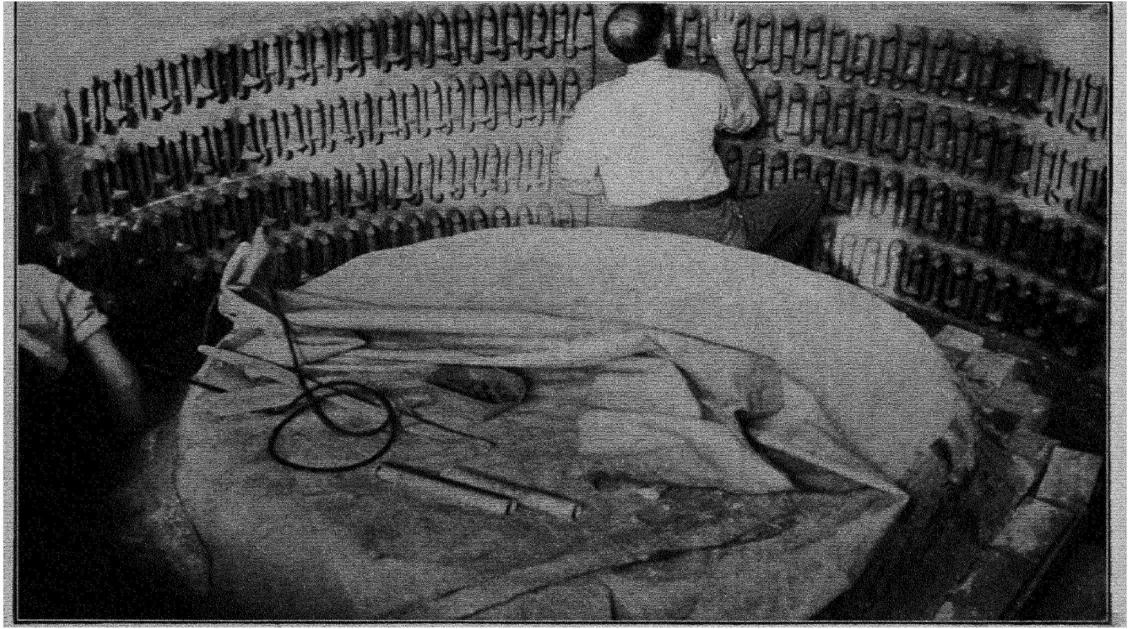

Fig. 42. 60-inch disc of fused silica in electric furnace.

tons. The 200-inch mirror will be approximately twice as thick and will weigh at least 30 tons, unless we decide to lighten it by using a ribbed structure for the underlying portion.

Everything depends upon the success of the mirror, and we are, therefore, considering as possible alternatives several entirely different methods of construction, some of which are very promising. Ritchey's cellular mirror has been considered, but none of our advisers favor its adoption because of the difficulty of figuring with optical perfection and cementing the thin glass faces and the edges of the intervening honeycomb, not to mention doubts as to the optical permanence of a heavy cemented structure subjected to wide ranges of temperature. The late Sir Charles Parsons took a great personal interest in our problem; and the experiments of his firm in making composite glass discs up to 3 feet in diameter, all the contiguous surfaces of which are fused together in the oven, without the optical complications just mentioned, are important. Our National Bureau of Standards, which recently produced a very fine mirror disc of solid glass over six feet in diameter, is experimenting along similar lines. Ribbed metallic discs of speculum metal, or an even better alloy, are also well worthy of consideration. A Dutch method of coating a metallic disc with glass of precisely the same coefficient of expansion, securely fused to its surface, is another process that has reached an interesting stage. Finally, there is every reason to believe that a 200-inch disc of special glass even less subject to distortion by temperature

changes than the well-known "Pyrex" can undoubtedly be made. Thus there are numerous possible alternatives in case fused quartz cannot be used for mirrors of the largest size.

After careful consideration by members of our Pasadena group, checked by the computations of our Research Associate, Doctor Frank E. Ross of the Yerkes Observatory, we have decided to make the focal length of the 200-inch mirror 55 feet, only 3.3 times its aperture. This is relatively shorter than that of the Hooker telescope, which has a focal length 5 times its aperture. The advantage of a focal ratio F:3.3, as users of "movie" cameras know, is to give an immense concentration of light with consequent reduction of exposure time. With this change of ratio, and a light-collecting area 4 times as great, the 200-inch telescope should prove fully 10 times as powerful as the Hooker telescope under similar atmospheric conditions.

A defect of short-focus mirrors is the small area of sharp definition in their focal plane. Outside of this area the star images, instead of being minute discs, resemble arrowheads pointing toward the centre of the field. Even a small area recording extremely faint stars is for many purposes far preferable to a larger field of sharp definition in which these feeble objects fail to appear. A notable illustration is afforded by the spiral nebulæ, where the problem of the nature, distance, and evolution of these extraordinary objects depends upon the detection of their constituent stars, now beyond our range except in

the case of two or three of the nearest of the spirals.

Three methods of enlarging the area of sharp definition have been found: the Schwarzschild and the Ritchey-Chrétien mirror systems, neither of which is applicable in our case; and the Ross correcting lens, which is placed in the cone of rays in front of the photographic plate. This lens, which has recently been developed by Doctor Ross as a part of our policy of improving all desirable devices for recording, measuring, or interpreting telescopic images, has given remarkable results when tested with the 60-inch reflector on Mount Wilson. Not content with an F:3.3 ratio, Doctor Ross has also computed a correcting lens which we hope will enable us to use the 200-inch mirror with an equivalent focal ratio of F:2.

In both of the above cases, as already stated, the photographic plate is supported directly in front of the 200-inch mirror, and centred on its optical axis. Another arrangement calls for the use of a convex mirror 60 inches in diameter, supported axially near the upper end of the telescope tube. This will change the ratio to F:10, and form a field of stars sharply defined over a photographic plate 17 inches in diameter, at a focus just below the 200-inch mirror, through the centre of which a circular hole will be cut. I need not pause to describe other mirror combinations required for different classes of photographic, spectrographic, and radiometric observations.

Turning now to the mechanical problem of mounting and moving these mirror systems with the extreme precision demanded, we fortunately find its solution

well within the range of modern engineering practice. When Lord Rosse built his 6-foot reflector in the 40's of the last century he was compelled to work on his country estate in Ireland without the aid of skilled opticians and machinists, or the methods and machine tools of modern engineering. In the present case we begin with twenty-five years of experience with large telescopes at Mount Wilson, and combine the knowledge of our local group of men of science and instrument builders with that of such skilled designers as Mr. Russell W. Porter of the Jones and Lamson Company of Springfield, Vermont, now an Associate of the California Institute; Messrs. Ambrose Swasey and E. P. Burrell of the Warner and Swasey Company of Cleveland, and Messrs. Gano Dunn and S. R. Jones of the J. G. White Engineering Corporation of New York. We have also been fortunate in having the benefit of the advice and criticism of such eminent authorities in Europe as Sir Herbert Jackson, Director of the British Scientic Instrument Research Association, and the late Sir Charles Parsons, son of Lord Rosse, distinguished not only for his work as an engineer, but also for his success in developing the most progressive optical glass and telescope building establishments in England. In this study of telescope mountings we are, therefore, pursuing the same co-operative policy as in all the other phases of the present undertaking.

Our decision in favor of an equatorial mounting, of which four types have been considered, is determined by our desire to command a wide range of the

heavens and the possibility it affords of producing celestial images by a single reflection from the 200-inch concave mirror. This is to be mounted at the base of a very stiff octagonal skeleton tube, about 24 feet in diameter and nearly 60 feet long, hung on bearings between the arms of a massive fork, which forms the upper end of a large polar axis, fixed parallel to the axis of the earth. The tube can be pointed electrically as far north as the pole (or beyond it) and far south of the equator. After being set at the angle determined by the declination of the celestial object, it is rotated east or west about the polar axis until the desired object is at the centre of the field. By the aid of the driving-clock the entire polar axis and tube are then turned slowly from east to west to counteract the effect of the earth's rotation and hold the celestial object in the field. Final corrections for the effect of the varying refraction of the earth's atmosphere are made by the observer, who watches stars at the edge of the plate through high-power eyepieces, and moves the plate by delicate mechanism so as to keep the guiding-stars at the intersection of cross-hairs in the eyepiece throughout the exposure, which may last for hours, or even be continued on several successive nights.

This fork type of equatorial mounting, which dates back more than a century, was built on a large scale (with a 4-foot mirror) by Lassell in 1861, and subsequently, with accurate driving-clocks and in somewhat different forms, by the fourth Earl of Rosse, by Common with 36-inch and 60-inch mirrors (the for-

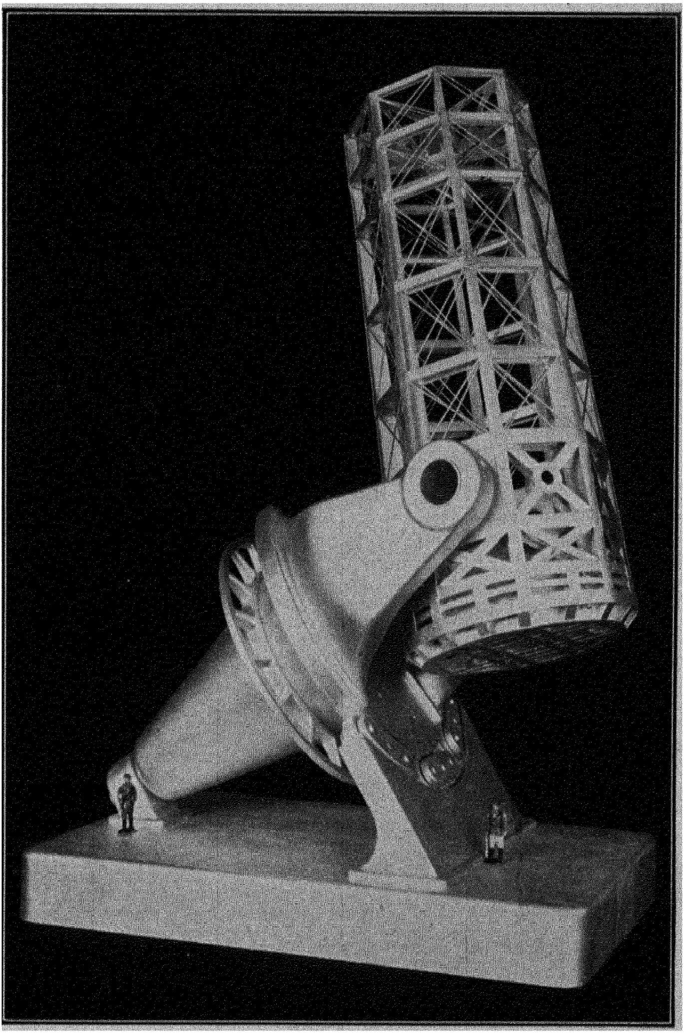

Fig. 43. Tentative design for the 200-inch telescope mounting.

mer afterwards used by Keeler and others at Mount Hamilton), and by Ritchey at Mount Wilson with a 60-inch mirror. A design closely resembling Lassell's, with heavy fork and polar axis and modern roller bearings to relieve friction, made by Doctor Pease in 1928, and a modified fork or "split-ring" design made by Mr. Porter, were carefully considered by our committee on the 200-inch telescope mounting. This committee included Mr. E. P. Burrell, Chief Engineer of the Warner and Swasey Company, who has made a provisional scale drawing and model of the fork type (Fig. 43), similar to that of Doctor Pease. When subjected to careful study and computations for flexure by Professors Epstein and Martel of the California Institute, and to further examination and criticism by Messrs. Gano Dunn and Samuel R. Jones of the J. G. White Engineering Corporation, this design was found to provide a very satisfactory solution of the general problem.

It is thus perfectly safe to proceed with our other plans, though much further criticism and study will be given both to the general design and its many details before the final working drawings are prepared. Our first necessity was merely to make sure of the possibility of one satisfactory general solution, which can of course be improved by further work. All such minor questions as suitable electric clamps, slow motions, etc., have been admirably solved before for such large instruments as the 72-inch Victoria telescope and the 100-inch Hooker telescope, and it simply remains to adapt the best of these, in the light of recent prog-

ress, to the needs of the 200-inch telescope. We now know beyond question that a tube and mirrors having a combined weight of 150 tons, involving a total weight for the moving parts of 500 tons, can be mounted equatorially and without troublesome flexure so as to afford access to the entire available sky, and manipulated with the ease and precision demanded by the delicate work in view.

POSSIBLE SITES

As compared with the microscopist, the astronomer is in some respects at a marked disadvantage. A small microscope can be brought to the limit of optical perfection at little expense and can be used almost anywhere under nearly perfect conditions. To improve our telescopes we must increase their size and their precision of construction, which means not only heavy expense in manufacture and operation but also added mechanical and optical difficulties. Moreover, instead of looking through homogeneous optical media, selected for the purpose in view, we must observe the stars from the depths of a turbulent atmosphere, which not only scatters and absorbs much of the light that reaches its upper levels, but so irregularly refracts the portion transmitted that the rays falling on the various parts of a large lens or mirror are rarely or never combined into a sharply defined and perfectly steady image.

By selecting a site of high altitude, above the denser and more disturbed portion of the atmosphere, in a region but little affected by clouds and storms, we may

greatly reduce these difficulties. In fact, as I stated in the first chapter, the conditions on Mount Wilson are so favorable that on a very large proportion of the nights in a year the 100-inch Hooker telescope gives us a gain in light-collecting power over the 60-inch telescope fully in proportion to its greater aperture. The use of the larger instrument has thus resulted in many fundamental discoveries beyond the range of the smaller one, and has more than justified our most sanguine hopes. Moreover, we have direct observational evidence that on Mount Wilson a 200-inch telescope could be depended upon to show a further gain, in keeping with its increased size. The probabilities now are that we can find a still better site within a short distance of Pasadena.

To understand the conditions required for the best results we must think of the appearance of the telescopic image of a star. Obviously, no clouds should be in the way, and our site should, therefore, be one where storms are few. But a clear sky is not enough. Under a magnifying power of, say, 500 diameters, the star image, instead of being a very minute and perfectly steady point, is usually enlarged and in a state of motion. The enlarged image oscillates very rapidly in all directions and also undergoes slower oscillations of about a second of arc in a period of approximately a minute of time, as Schlesinger has shown. As already stated, the observer is constantly correcting the position of the photographic plate during its exposure in order to reduce the effect of such tremors. But there is a limit to his quickness and

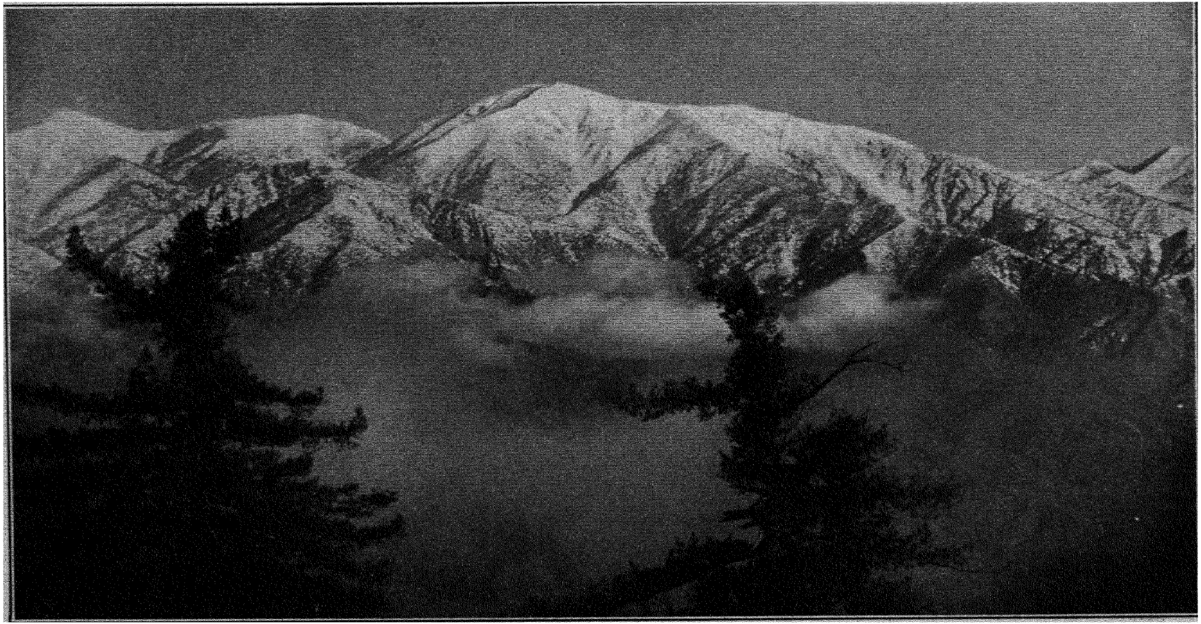

Fig. 44. Mount San Antonio as seen from Mount Wilson. Photographed with tele-photo lens.

skill, and the more rapid oscillations that escape him are consequently registered upon the plate. As these take place in all directions, the resultant image is nearly circular in form. Such a recorded image, which of course differs from the instantaneous moving image seen by the observer, has been well named by Newall a "tremor disc." Its diameter varies from several seconds of arc to about five or six tenths of a second, the smallest, I think, yet photographed. These minute images were obtained by Hubble under good atmospheric conditions with the 100-inch telescope on Mount Wilson.

If the telescope were optically and mechanically perfect, in correct adjustment, and provided with a perfectly controlled driving-clock, the star images would of course remain fixed on the plate if there were no atmosphere to interfere. There would be no tremor discs, and the fainter stars would be registered as extremely minute points. Brighter stars on the same plate would be larger, as there is a purely photographic effect that causes a gradual spreading of the light in the sensitive film about the central point, producing a disc which increases in diameter with the length of the exposure and the brightness of the star.

The importance of securing the smallest possible star images will be recognized when it is remembered that perfect concentration of all the light in a point would permit the registration of stars too faint to affect the plate if their feeble rays were scattered over the much larger area of the tremor disc. Another advantage of perfect concentration would be the possi-

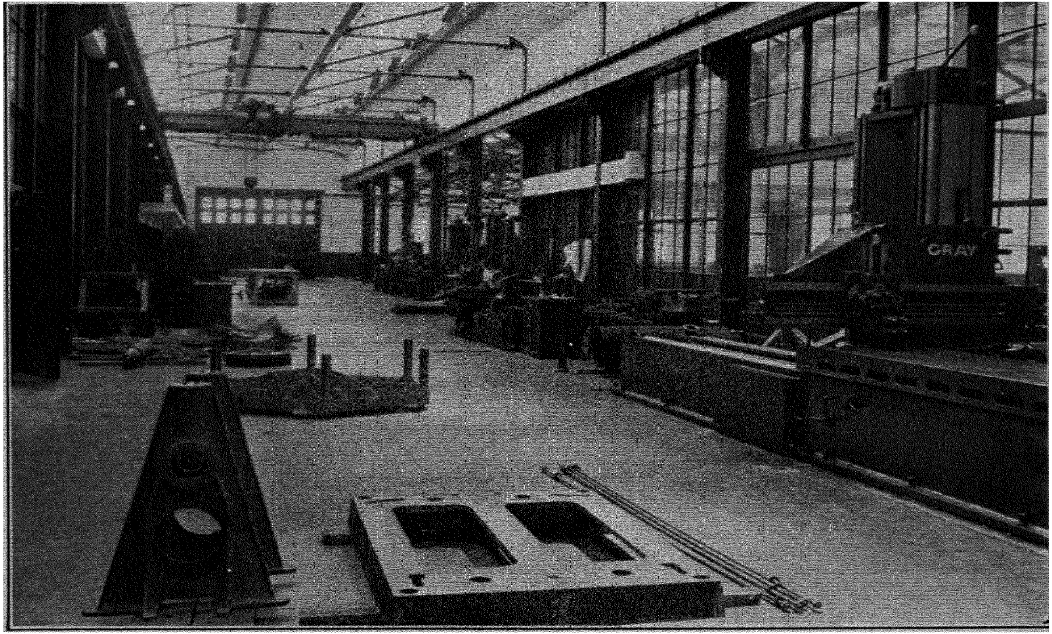

Fig. 45. Astrophysical Machine Shop, California Institute of Technology.

bility of distinguishing and measuring two closely adjacent stars of a pair, or the minute details of planetary or nebular structure which would overlap and be confused if enlarged by atmospheric disturbance.

It rarely happens that an observatory site can be selected without regard to geographical limitations. When the Carnegie Institution of Washington was established, however, it was decided to locate its various departments of research in places where their work could be done to the best advantage. Accordingly, the Observatory Committee, of which I was a member, was authorized to send a skilled observer to a large number of promising sites, armed with a telescope sufficiently powerful to enable him to make reliable comparative tests. We selected the late Professor Hussey, then of the Lick Observatory, where the splendid results obtained on Mount Hamilton had opened the eyes of astronomers to the excellent atmospheric conditions available in California. As the result of his observations in 1903 at many points in California, Arizona, and Australia, confirmed by our own longer series of tests in the following year, we selected Mount Wilson, in the Sierra Madre range a few miles north of Pasadena, as the most promising site for our purpose.

It is easy to understand the astronomical advantages of this region of the southwest, where we photograph the sun on more than three hundred days of each year. In choosing the most suitable site for a large telescope we are limited by three principal restrictions: latitude, altitude, and weather. If we go too far from the

equator we lose the broad zone of stars beyond it; while if we approach it too closely we cannot observe the stars near the pole at a sufficient height above the horizon to afford good images. A latitude of from 30° to 35°, from which about three-fourths of the entire celestial sphere can be effectively observed, is most suitable. As for the altitude of the site, it should be great enough to escape the absorption and irregular refraction of the denser part of the atmosphere, but not so great as to involve excessive snowfall and extreme winter temperatures. An elevation of from 6,000 to 8,000 feet seems to be most favorable in Southern California. The weather enters in several ways. A great range of temperature, daily or annual, affects the form of exposed optical surfaces and the efficiency of the observer, who cannot nimbly and precisely operate micrometers, double-slide-plate-holders and other devices when his fingers are stiff with cold or hampered by heavy gloves. But the most serious effects of the weather are cloudiness, large tremor discs caused by air disturbances felt far beyond the central cloudy area of storms, and winds that shake the telescope and thus displace star images.

There are several types of widespread storms in the United States, two of which are most common. These are the large cyclones (not tornadoes) whose centres move eastward from the Pacific Ocean across the country near the Canadian border, and northward near the Atlantic coast from the Caribbean Sea. Taking these and all other factors into account, our choice is narrowed to the lofty plateaus and mountain ranges

in the southwestern part of the country. Indeed, the astronomer and physicist may well regard this favored region as a vast high-level laboratory, admirably designed to meet their varied needs. During the protracted dry season in Southern California we are able to carry on the many types of astronomical work that call for daily observations in long unbroken sequences. Once, for example, in a spectroscopic study of the general magnetic field of the sun, photographs were taken at Mount Wilson on more than ninety successive days. Clear and tranquil nights are even more common; and a comparison of the total number of hours of observation with those of eastern observatories shows a great preponderance. Measured in other terms, such as average size of tremor disc, low wind velocities, or favorable temperatures, the advantages are equally apparent. Thus our experience here of twenty-eight years, with telescopes of all sizes and types, will serve as a sound basis for comparative studies of other possible sites.

Physicists as well as astronomers have profited by the mountain laboratories, extending up to 12,000 feet, within easy reach of Pasadena. Michelson repeatedly used Mount Wilson for his measures of the velocity of light, sending intermittent flashes to a large mirror about 22 miles distant on Mount San Antonio, which returned them to his point of observation. Here, too, with the aid of Pease and Anderson, he developed his interferometer from a small laboratory instrument into a 20-foot auxiliary of the 100-inch telescope, the first successful device for measur-

ing the diameter of a star. Here he and others have repeated the famous Michelson-Morley experiment, forerunner of the Einstein theory, to determine beyond doubt whether his original negative result might

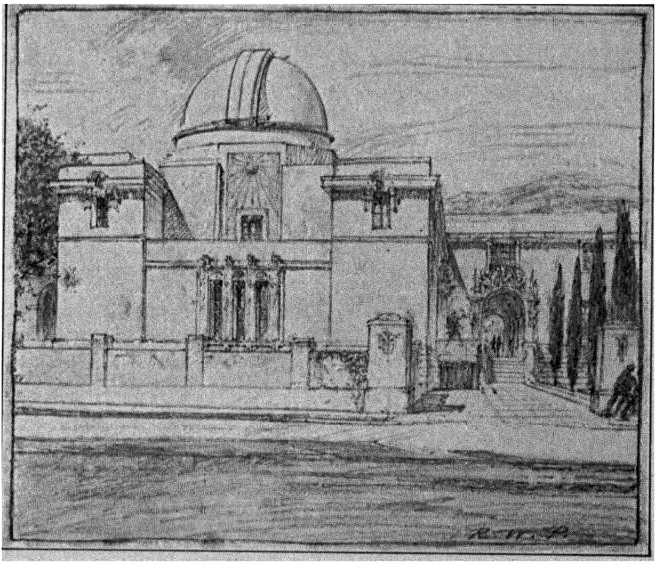

Fig. 46. Astrophysical Laboratory, California Institute of Technology. From a preliminary sketch by Porter after the architect's design.

be affected by the altitude of the apparatus. Millikan has made no less use of neighboring high-level stations. Within four hours' motor ride of his Pasadena Laboratory is a mountain lake, containing radium-free water, in which he and Cameron have measured the penetrating power of the cosmic rays with delicate electrometers sunk to depths as great as 150 feet. When

they wish to check their results at still higher levels, they easily find suitable lakes among the lofty Sierra peaks farther north. One of these lakes lies within a narrow gorge, whose towering walls serve to exclude from the electrometer all cosmic rays except those coming from a narrow strip of sky overhead. Aided by this natural telescope, they have found that the Milky Way is no richer in cosmic rays than all other regions of the heavens far from the galactic plane.

These illustrations, which are drawn from our recent co-operative work, help to emphasize the most important factor entering into the selection of a site for the 200-inch telescope. To be efficient, it must of course be placed where the atmospheric conditions are excellent. But its efficiency and output can be multiplied several fold by establishing it within convenient reach of Pasadena, where the activities of the California Institute and the Mount Wilson Observatory are centred. Only in this way can the great advantages resulting from the intimate co-operation of the research staffs and the utilization of existing equipment be realized.

A preliminary comparative study of many promising sites in Southern California and Arizona is now being made under the direction of Doctor J. A. Anderson, Executive Officer of the Observatory Council of the California Institute. The customary plan of merely estimating the quality of the star image, on a scale in which 0 stands for very bad, 5 for good, and 10 for ideal perfection, has been replaced by a method of measuring the diameter of the tremor disc, devised

by Doctor Anderson, and thoroughly tested with small telescopes on Mount Wilson in co-operation with ob-

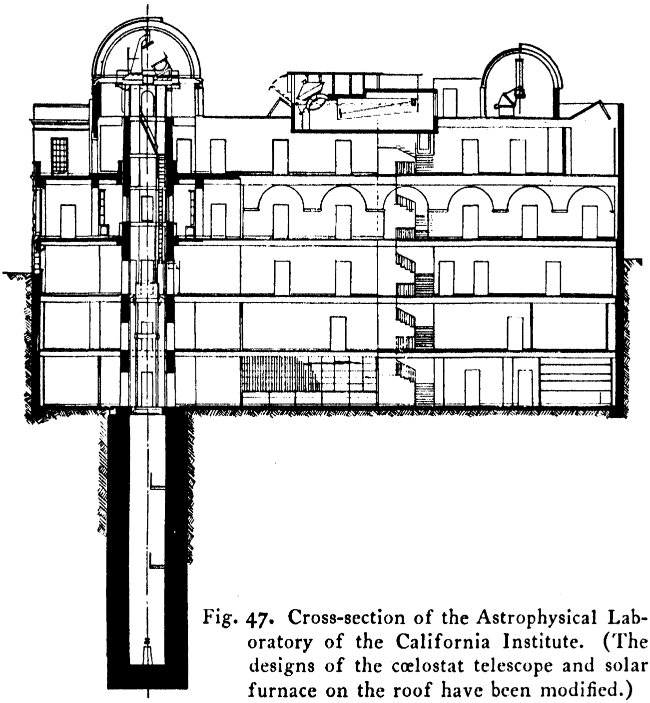

Fig. 47. Cross-section of the Astrophysical Laboratory of the California Institute. (The designs of the cœlostat telescope and solar furnace on the roof have been modified.)

servers working simultaneously with the 60-inch and 100-inch reflectors. Ten portable telescopes equipped with this device have been used simultaneously for long periods of time at as many different sites. Our choice has been narrowed down to a few most favor-

able regions, where it may be necessary to continue the comparative tests for two or three years before making a final selection.

AUXILIARY INSTRUMENTS

Our experience at Mount Wilson has clearly shown that the 200-inch telescope should not be confined to a single class of work, but should be quickly adaptable for a wide variety of observations. Its efficiency will depend quite as much upon the perfection of the photographic plates, spectrographs, thermocouples, photo-electric cells, laboratory apparatus, and many other devices used to record, measure, and interpret the images of celestial objects as upon the size and quality of the telescope that produces them. Moreover, I have learned from forty years of astrophysical research that many forms of auxiliary apparatus and laboratory equipment, not of standard type, should not only be designed and constructed under the personal supervision of those who use them, but constantly improved in the light of new discoveries. Thus adequate laboratories and instrument shops are as necessary to an observatory that effectively combines astronomy with physics and chemistry as they are to such corporations as the American Telephone and Telegraph Company and the General Electric Company, whose rapid advancement is the direct result of their development of new devices through research.

There is nothing novel in this method to the physicist and the physical chemist, who are constantly build-

ing, adapting, and improving their instrumental means. It naturally found little recognition, however, in observatories equipped with standard apparatus, easily obtainable from commercial instrument-makers, and necessarily used without change for long periods of time. But with the rise of astrophysics the point of view and the methods of the physicist and chemist have been gradually added to those of the astronomer, to the great advantage of all concerned.

This policy applies equally to small and large observatories, as I found when a boy, working with a little lathe, a small spectroscope and induction coil, and a 4-inch telescope; later at the Kenwood Observatory, where I had some good machine tools; and subsequently at the Yerkes Observatory, where these machine tools served as the nucleus of a shop in which we built a large part of our instrumental equipment, with the aid of small gifts from the Rumford and Draper Funds and from several friends.

I could give scores of illustrations from our experience at Pasadena and Mount Wilson, where our shops and laboratories, supplying the very life-blood of the Observatory, have been run to full capacity since their beginning in 1904. Electric arcs, sparks, vacuum tubes, furnaces, and other light-sources, frequently improved in the light of astronomical demands or physical discoveries, have been used constantly from the first, with results of vital importance. When equipping the original laboratory I ventured to include a large electromagnet and polarizing apparatus, recognizing that they would at least be useful in

classifying spectral lines. Three years later they proved to be the indispensable means of identifying and studying magnetic phenomena in the sun. The temperature classification of spectral lines, the development of a new method of measuring stellar distances, the analysis of solar and stellar atmospheres at various levels, the precise measurement of standard lines and solar spectrum wave-lengths and the determination of the Einstein effect in the sun, the discovery of new elements and new isotopes in celestial sources, the first use of the microphotometer in astronomical work, Michelson's application of the interferometer for measuring star diameters, the development of large reflecting telescopes, the tower telescope in various forms, vacuum thermocouples and radiometers for measuring stellar and planetary radiation, spectroscopes, spectroheliographs, and spectrohelioscopes of many types, apparatus for the ultra-violet measurement of fluctuations in solar radiation, means for the study of stellar spectra under high dispersion—these are some conspicuous instances of the advantages at Mount Wilson of utilizing shops, laboratories, telescopes, and their accessories in the most intimate union.

The recognition of these advantages by the Rockefeller Boards has enabled us to plan the Astrophysical Observatory of the California Institute so as to supplement and extend our present combined facilities. The Astrophysical Laboratory, now nearing completion on the grounds of the California Institute, will serve for the Pasadena headquarters of the resident and visiting astronomers and physicists, the measure-

ment and reduction of photographs taken with the 200-inch telescope at its mountain site, the performance of experiments for the interpretation of these observations with the aid of instruments and methods available neither in the Bridge and Gates Laboratories of the Institute nor in the laboratories of the Mount Wilson Observatory, and for the work of the Graduate School of Astrophysics. Here, too, will be devised the new instruments and methods which the neighboring Machine and Optical Shops will enable us to build and modify as experience suggests.

The scale of these shops is necessarily determined by the work to be done in them, and this depends, in turn, upon the scale of the 200-inch telescope. The largest parts of the telescope mounting, which demand the use of huge boring mills, planers, and other machine tools of great capacity, will not be constructed here. These can be built once for all in commercial machine shops, as they do not require the frequent modifications often necessary, for example, in large auxiliary instruments during their period of development. In general, standard instruments will be purchased, whenever possible, from commercial makers; large machine work will be entrusted to commercial shops competent to produce it with the necessary precision; and the capacity of our own shops will be determined in the light of our Mount Wilson experience.

The Machine and Instrument Shop was completed in 1930, and much work has been accomplished in it (Figs. 45, 49, 50). As the optical work on the 200-

inch and other mirror discs must be done by our own opticians, the Optical Shop must be built on a larger scale. This is evident when the diameter and weight of the 200-inch disc and its auxiliary mirrors, and the consequent size of the grinding and polishing machinery are borne in mind. We at first considered the advisability of erecting this Optical Shop at the mountain site of the telescope; but it must be close to the Machine Shop, and this in turn must be near the Astrophysical Laboratory. Moreover, the advantage of using the heating and power plants of the California Institute, and several other important arguments, leave no doubt as to the desirability of building the Optical Shop in Pasadena. The 200-inch mirror disc will be made at the Thomson Research Laboratory, or some other point where adequate facilities for the work are available, and then shipped to Pasadena in its rough state, for grinding and figuring.

When I began photographic work with microscope and telescope in the early eighties all commercial plates were insensitive to yellow and red light. To sensitize them for the yellow, a few years later we bathed them in a solution of erythrosin. It was not until early in the present century that plates sufficiently sensitive in the red to serve for the photography of the hydrogen atmosphere of the sun became available. Since then the advance has continued far into the invisible infra-red, recently enabling Babcock in the Mount Wilson Laboratory to discover lines of fundamental importance to our knowledge of the sun. We owe these infra-red plates, invaluable for the study of

a host of astrophysical, physical, and chemical phenomena, to the activities of the Eastman Research Laboratory under the direction of Doctor C. E. K. Mees. Here, with the cordial approval of both Mr. George Eastman and Doctor Mees, many other problems of vital importance to the 200-inch telescope are sure to find their solution.

Foremost of these is the production of plates of the highest sensitiveness combined with very fine grain. A star image on the most sensitive plates now available commercially looks under high magnification like a heap of coarse sand. For this reason we are compelled to employ slower plates, of finer grain, for many kinds of work, thus greatly increasing the necessary exposure time and virtually diminishing the size and output of the telescope. These illustrations will suffice to indicate the importance of improving the many photographic processes required for astrophysical research.

The fable that Archimedes set fire to the Roman ships at Syracuse by focussing upon them the sun's rays has found more substantial applications in modern times. Large burning lenses and concave mirrors were long ago used to perform chemical experiments and to vaporize metals, and recently Straubel of the Carl Zeiss Company has found it possible to obtain a temperature of nearly 5,000° Centigrade (9,000° Fahrenheit) at the focus of a searchlight mirror. As this will instantly vaporize tungsten and is within about 1,000° of the surface temperature of the sun, a properly designed "solar furnace" should be of great service in extending the range of our electric furnaces,

so successfully used by King and others for the spectroscopic interpretation of astrophysical phenomena. We are accordingly building a large solar furnace, designed by Anderson and Porter, for use in our new Astrophysical Laboratory (Figs. 48, 49, 50).

If space were available, I might go on to describe other instrumental improvements already under investigation, as well as our plans for theoretical researches, and the development of a graduate school of astrophysics. I must confine myself, however, to a single illustration.

Several years ago Slipher found that the nearer spiral nebulæ appear to be moving at velocities much higher than those of any objects within our galactic system. Hubble, as a part of a general study of nebulæ, was able to push his investigations to much greater distances through the aid of the 100-inch telescope on Mount Wilson. Aided by Humason, he found that the apparent velocities of these extra-galactic nebulæ increased with their distance. He was hampered, however, by the limitations of his spectrographs. For such work their efficiency depends upon the use of camera lenses of the shortest possible focal length. The best "movie" lenses obtainable in this country or abroad were tested, but they were not found to be fast enough to record the spectra of the extremely remote nebulæ needed to determine adequately the validity of his tentative conclusion.

At this juncture the 200-inch telescope project was undertaken. It was clear that the space-penetrating power of the new telescope might be enormously in-

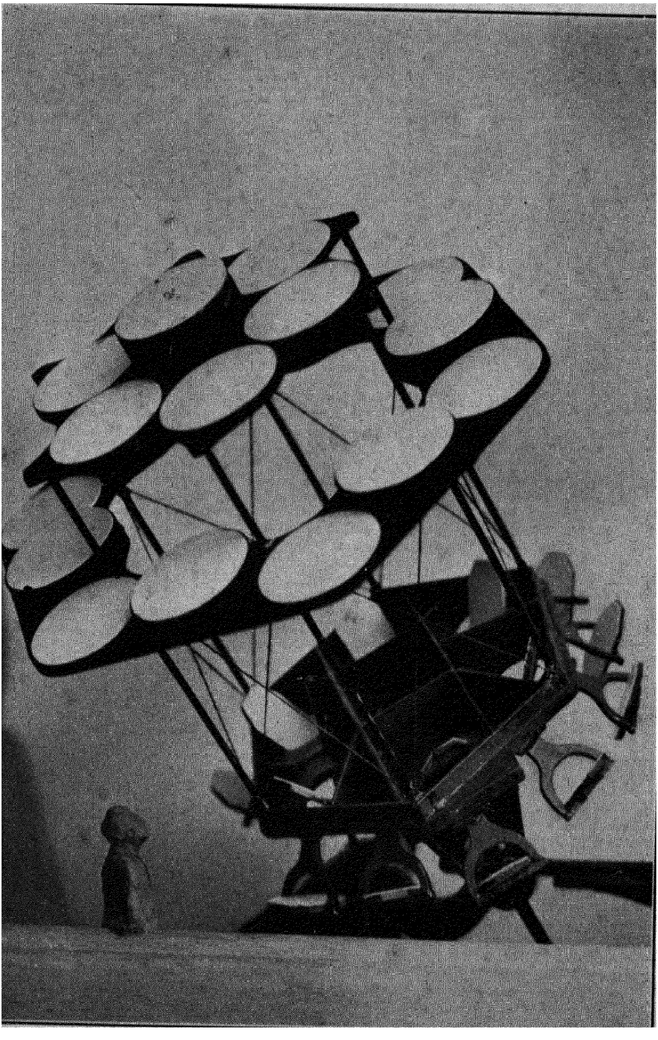

Fig. 48. Model of solar furnace. 19 single lenses, each 24 inches in diameter, used in combination with 18 smaller plane mirrors and 19 condensing lenses, concentrate sunlight within a vacuum chamber, where metals can be vaporized and studied with a spectrograph.

creased by means of still better camera lenses for its spectrographs. Mr. W. B. Rayton, optical expert of the Bausch & Lomb Company, when consulted by Doctor Anderson, suggested the use of a new type of lens designed on the principle of a microscope objective. The Bausch & Lomb Company accordingly made for us a remarkable lens of 2 inches aperture and only 1 5/16 inches focal length, or a focal ratio of F:0.6. No lens approaching this in speed has ever been made for moving-picture work.

Tests made by Humason with the 100-inch telescope showed excellent definition and a gain of 50 per cent in speed over the best lenses previously used. It thus became possible to photograph the spectra of extremely remote nebulæ.

The results of the joint work of Hubble and Humason are illustrated in Figs. 55 and 56. The original nebular spectra, only about one-eighth of an inch long, have been enlarged and widened, while above and below each appear the fixed lines of the comparison spectrum (Fig. 56). The top spectrum is that of the sun, with the two broad H and K lines of calcium (indicated by an arrow) in their normal position. In the second spectrum these lines are shifted toward the red, by an amount indicating a velocity of 3,000 miles per second. The nebula itself (N. G. C. 385) is shown to the right of the spectrum. The succeeding photographs show greater and greater shifts, corresponding to velocities of 4,200, 7,300 and 12,000 miles per second, respectively. As their images to the right indicate, these nebulæ are increasingly fainter

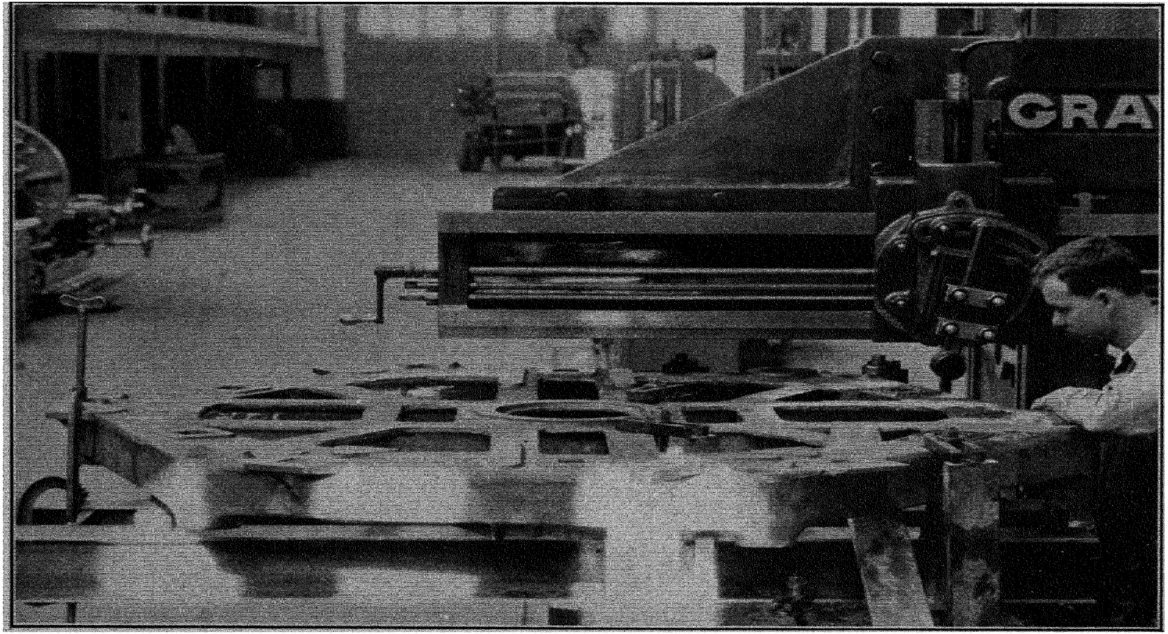

Fig. 49. Planing a casting for the solar furnace mounting in the Astrophysical Machine Shop.

and smaller. Hubble has shown that the distance of such nebulæ can be measured by their brightness. He has accordingly determined that the apparent velocity increases in direct proportion to the distance, at the

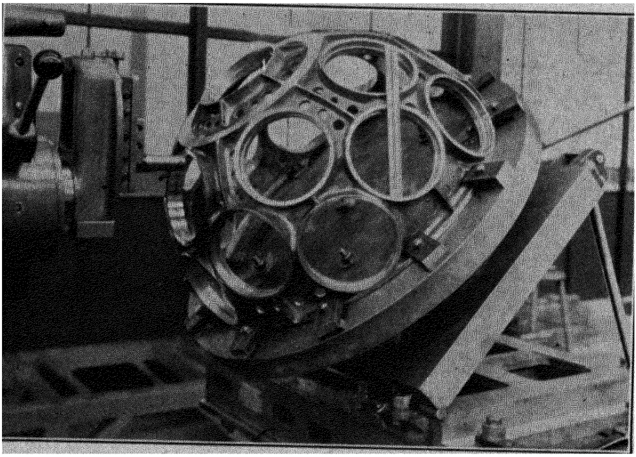

Fig. 50. Boring the cells for the condensing lenses of the solar furnace.

rate of 100 miles per second per one million light-years of distance.

This remarkable result has led to the recent discussions of Einstein, de Sitter, Lemaitre, Jeans, Eddington, Tolman, Zwicky, and others on the "expanding" universe. If the entire displacement of the H and K lines is due to motion, the original Einstein universe must have had a radius of about 1,200 million light-years (Eddington), which has now increased to something like 2,000 million light-years (de Sitter), and is still expanding.

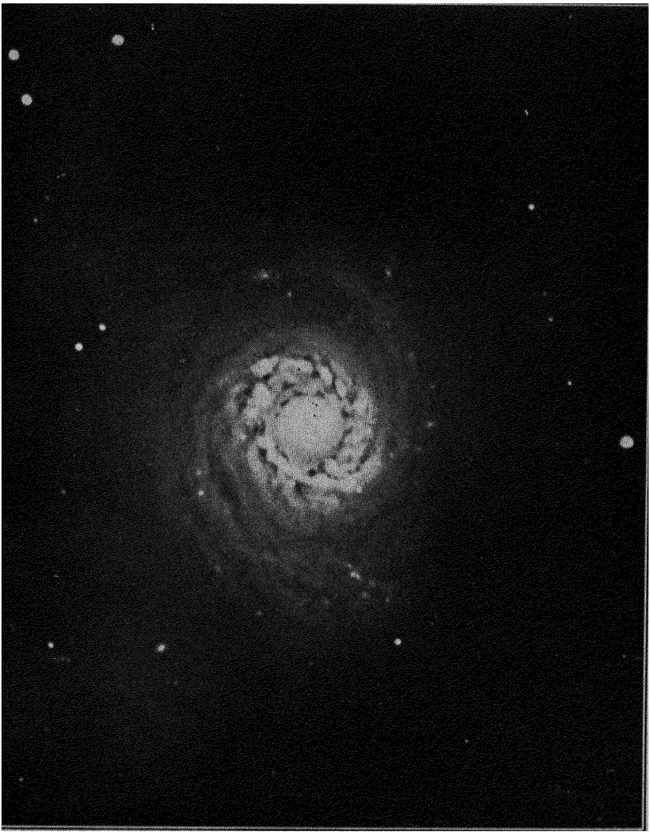

Fig. 51. Spiral nebula N. G. C. 4736. (Pease.) Distance 1½ million light-years.

There are strong reasons to doubt, however, whether this conclusion is strictly correct. As Jeans has stated, these figures would fix the age of the universe at about 1,000 million years, which appears to be less than the age of the earth. Moreover, much evidence

points to stellar ages of millions of millions of years. Nevertheless, the theories of both de Sitter and Lemaitre demand an expanding universe, while other physical causes may explain a large part of the shift of

Fig. 52. Spiral nebula N. G. C. 1068. (Pease.) Distance 3 million light-years.

the spectral lines. Thus Zwicky ascribes practically all of the shift to the effect on light of gravitating matter scattered through space. All authorities agree, however, that the great penetration of the 200-inch telescope, increased 50 per cent by Rayton's lens, will prove a prime factor in the solution of this problem, which belongs equally to astronomy and physics.

The success of the whole undertaking obviously depends upon the initiation and development of a wise

policy of design, construction, and operation, and the provision of the necessary financial support. As for the latter, an adequate income has been assured for the early operation of the Astrophysical Laboratory

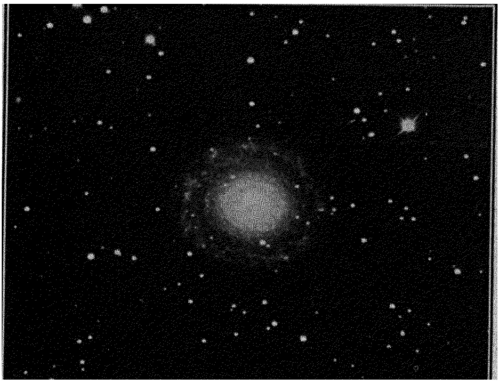

Fig. 53. Spiral nebula N. G. C. 7217. (Pease.) Distance 6½ million light-years.

and Graduate School of Astrophysics, and a much larger sum is promised for the work of the Observatory when completed. The Observatory Council, in charge of the entire project, includes Henry M. Robinson, best known internationally as one of the authors of the Dawes plan and as a leading representative of the United States at Versailles and Geneva; Robert A. Millikan, whose studies of the cosmic rays and the structure and radiation of the atom are organically related to the astrophysical researches in view; Arthur A. Noyes, whose physico-chemical investigations also enter directly into our general attack on the cosmic

phenomena and the constitution of matter; and the writer. Doctor John A. Anderson, Executive Officer of the Observatory Council, is as widely recog-

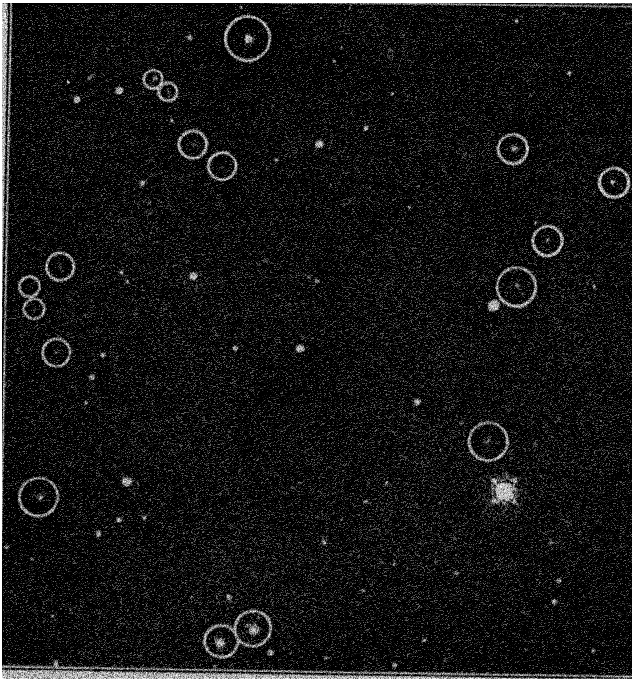

Fig. 54. Cluster of remote nebulæ in Leo. (Christie.)

nized for his skill in devising optical instruments as for his investigations made with their aid. The Advisory Committee, headed by Doctor Walter S. Adams, which works in the closest relations with the Observatory Council, and the list of our other advisers in this

country and abroad, include many authorities in various fields of science and engineering.

Certain minds of the "practical" type, regardless of the attitude of our greatest statesmen and industrial leaders and unconscious of the history of constructive thought, sometimes raise the old question, *cui bono?* What is the good of astronomy or, indeed, of any form of pure science? I have already attempted to answer the general question in a paper in *Harper's Magazine* entitled "Science and the Wealth of Nations," but a more specific reference to astronomy and especially to the value of large telescopes may appropriately close the present volume.

Look back over sixty centuries and see the Egyptian priests nightly observing the heavens from the summits of their temples. Like a vast clock, the celestial sphere, turning from east to west, marked by the meridian passage of familiar stars the hours for their devotions and the months of their simple but essential calendar. From these crude beginnings arose the precise measurement of time and the regulation of the calendar, our accurate methods of surveying and mapping the face of the earth, and our safe means of navigating both sea and air.

To realize our larger debt to astronomy read Henri Poincaré's book, "The Value of Science." The basis of science is the knowledge of natural law, and we owe the conquest of law to astronomy. Where would our modern civilization be, asks Poincaré, if the earth, like Jupiter, had always been enveloped in clouds? Our remote ancestors were creatures of superstition,

surrounded by mysteries, startled at every display of incomprehensible forces, accustomed to attribute all natural phenomena to the caprice of good and evil spirits. To-day we no longer implore the aid of genii,

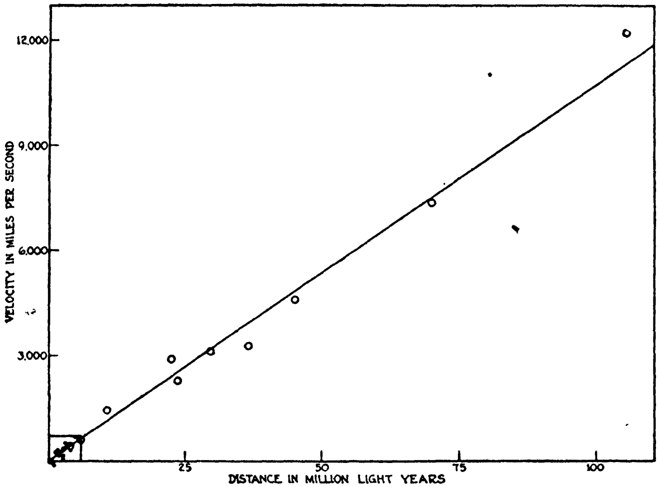

Fig. 55. Diagram showing the proportional increase of nebular velocity with distance. The small black dots in the lower left-hand corner represent the only available observations up to 1928. The open circles represent recent observations. (Hubble and Humason.)

but utilize natural laws, of which we are constantly learning more. Recognizing, as we do, the unchangeable basis of these laws, we do not foolishly demand that they be changed, but submit ourselves to them, and use them for the advantage of mankind.

Astronomy taught us the existence of the laws of nature. The Chaldeans, observing the heavens even more attentively than the Egyptians, perceived har-

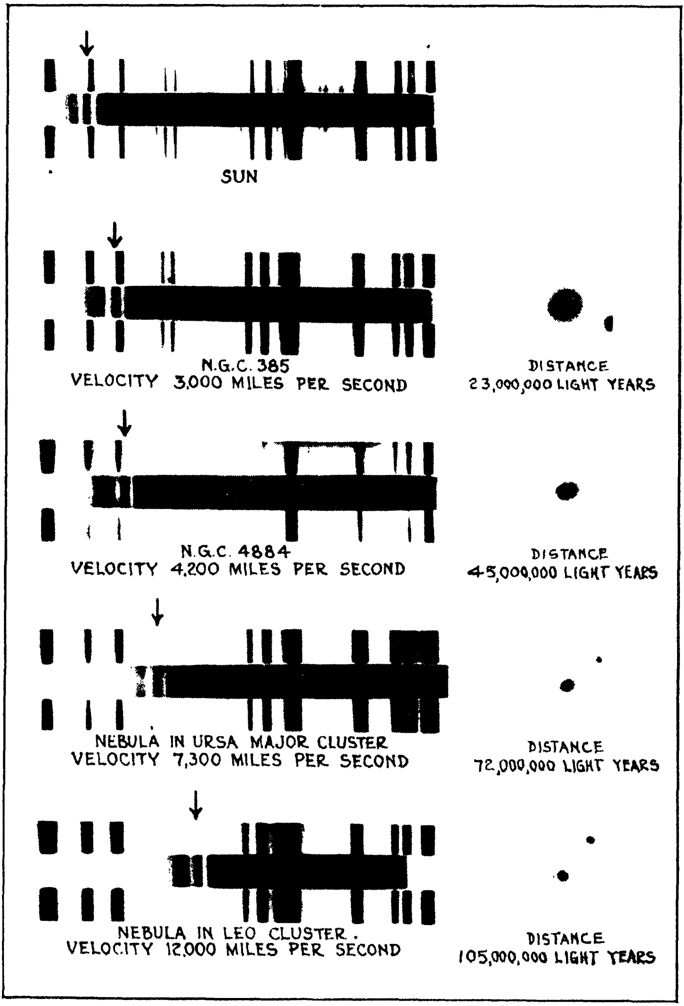

Fig. 56. Spectra of four remote nebulæ at increasing distances, showing corresponding increase of velocity. The nebulæ appear at the right. (Humason.)

mony of motion and sequence of phenomena. Day and night, the round of the seasons, the phases of the moon, the periodic wanderings of the planets held their attention and encouraged their study. Their work was continued by the Greek astronomers, who discovered law after law with the simple instruments at their command. Copernicus, Kepler, and Galileo fixed the sun at the centre of our system, shattered the mediæval mode of thought, and prepared the way for Newton, who finally announced the most general of all natural laws.

Encouraged by these never-ending successes, students turned their attention to the phenomena of the earth's surface, and found in their apparent disorder the same harmony and the same reign of law. But the infinite variety of nature, the conflict of forces, and the extreme complexity of terrestrial phenomena would have greatly delayed progress if the simple and easily-discovered laws, emblazoned on the heavens, had not pointed the way. Faced with discouragement, the physicist or the zoologist could fall back upon the assurance, which astronomy had repeatedly afforded, that nature does obey laws. Their task, therefore, was to discover these laws, and to persist in their endeavors until the difficulties had been overcome.

To the astronomical and physical researches of Galileo we are chiefly indebted for our escape from the magic and superstition of the past. But we owe him a larger debt. His telescope, followed by others of increasing power, pushed back the hampering boundaries of the universe and advanced step by step into

larger and larger spheres, where the same laws are found to reign, unbroken by distance or by time. Thus arose a new and vast conception of an ordered cosmos, involving the countless spiral nebulæ far beyond our own galactic island, in which the solar system is as a grain of sand. In this conception we may glimpse the imprint of a Creator, infinitely above the tribal deities of early man, whose immutable laws it is our first duty and greatest advantage to discover and to obey.

During our own time spectrum analysis, initiated by Kirchhoff's study of the sun, has revealed the unity of terrestrial and celestial substance and provided the means of tracing the evolution of stars and nebulæ and the systems in which they are grouped. Moreover, it has served as our guide to the true nature of matter and the advancement of the fundamental sciences of physics and chemistry. The first harmonic series of spectrum lines and the first ionized atoms (lacking one or more electrons), vital clues to the modern theory of matter, were found in the sun and stars. Quickly, with the aid of powerful telescopes, the vast experiments performed for us in these celestial laboratories have added to basic knowledge. The three most vital tests of the Einstein theory can be made only with the telescope. Matter 2,000 times as dense as platinum has been found in the companion of Sirius. Oxygen and nitrogen in "forbidden" forms have been detected in the excessively rare gases of the Great Nebula of Orion. The transformation of matter into radiation, predicted by physical theory, is at-

tested by stellar observations. And now we may hope that the complex problem of the expanding universe may be settled by theoretical investigations based upon celestial measurements. Can one doubt that a telescope powerful enough to carry all these studies far beyond our present possibilities will prove profitable, not merely to the astronomer but to the physicist, the chemist, and to all who utilize the results of science in the many-sided problems of modern life?